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MHR F-1471

40-kW Field Test Power Plant Modification and Development

Phase II

Annual Report

MASTER

FCR-2067

Period of Performance - July 1, 1978 thru June 30, 1979

DOE Contract No. DE-AC-01-77 ET11302
(Formerly ET-77-C-03-1471)
GRI Contract No. 5010-344-0060

Prepared for

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Date: 8/15/80

UNITED TECHNOLOGIES.
POWER SYSTEMS DIVISION
FUEL CELL OPERATIONS
P.O. Box 109, South Windsor, Connecticut 06074

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BACKGROUND AND INTRODUCTION

Fuel cell power plants electrochemically convert fuel such as pipeline gas, coal gas or liquid, or biomass gas directly into conventional electricity and heat. A power plant consists of three major subsystems: a fuel processor to clean and convert the fuel to hydrogen and carbon dioxide, a cell stack to electrochemically convert hydrogen and oxygen from air to direct current electricity, and an inverter to change this electricity to conventional AC, Figure 1.

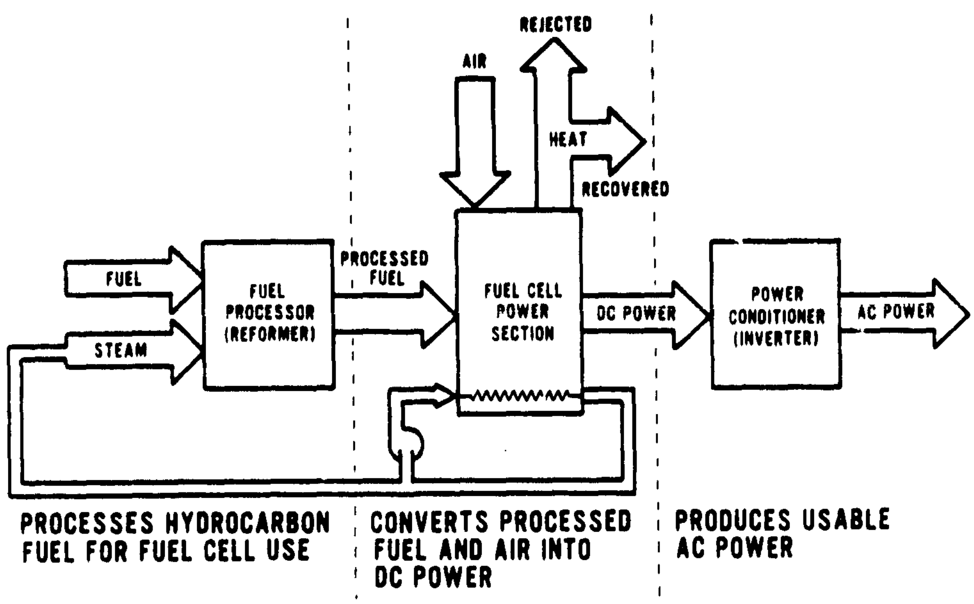


Figure 1. Fuel Cell Power Plant

Following the test of a 4-kW experimental fuel cell power plant by Columbia Gas Systems in 1966, thirty gas utilities formed a not-for-profit corporation called TARGET (Team to Advance Gas Energy Transformation) to support fuel cell research at United Technologies Corporation (UTC). During 1971-73 some 65 experimental 12.5-kw fuel cell power plants, designed and built by UTC, were installed and operated by gas and combination utilities in 35 on-site locations, Figure 2, to determine the conceptual feasibility of on-site fuel cell electric service. This experimental power plant fabrication, installation, operation, and maintenance experience, together with the results from the concurrent market, economic, code,

regulatory, and other investigations identified a number of deficiencies and system requirements which provided the objectives and direction for the continuing effort.

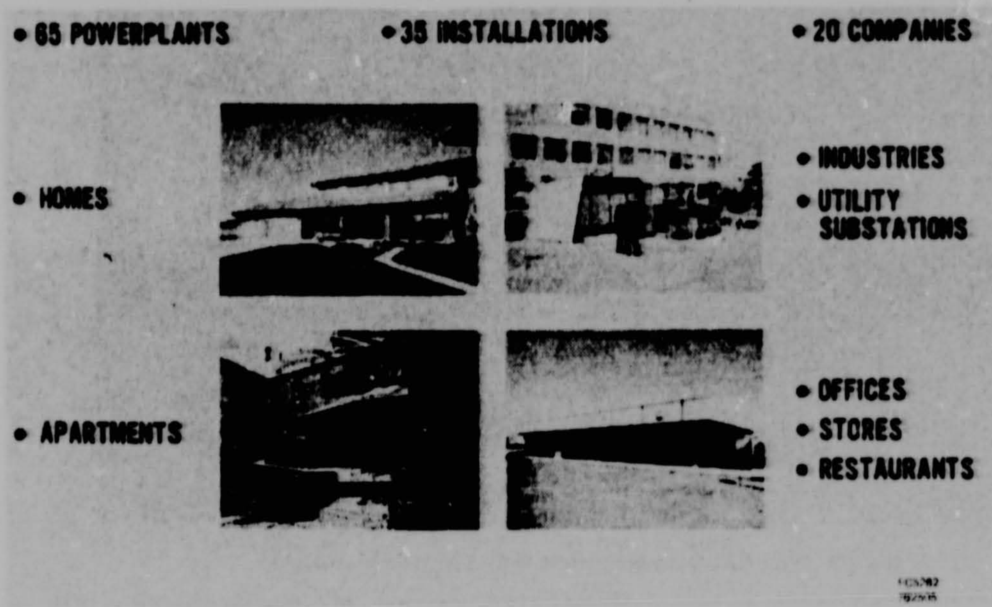
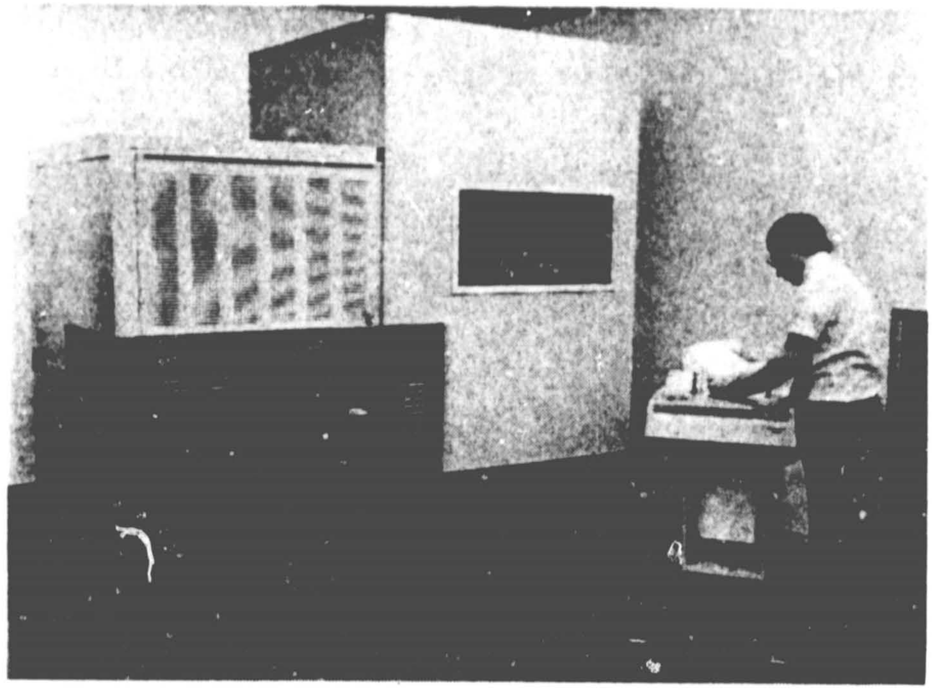


Figure 2. Field Testing of On-Site Power Plant

In 1976 a relatively sophisticated 40-kW experimental unit, reflecting lessons learned from the previous comprehensive field tests, successfully demonstrated broad band 40% electrical generating efficiency and the availability of power plant waste heat at useful temperatures. This experimental power plant is shown in Figure 3. The combined output of electricity and heat exceeded 80% overall pipeline gas utilization, Figure 4, in contrast to about 30% utilization for traditional approaches for electric generation and 60% utilization for space and water heating.

An even higher level utilization level was achieved in testing involving a simulated 16-unit apartment building Figure 5. When typical New England winter conditions were simulated and a heat pump was included with the heat recovery system, less gas energy was used to produce all the energy requirements of the building -- electricity and heat -- than was needed by a conventional gas-fired furnace to provide heat alone.



(WCN-4505)

Figure 3. Fuel Cell Demonstration Room in UTC Facility

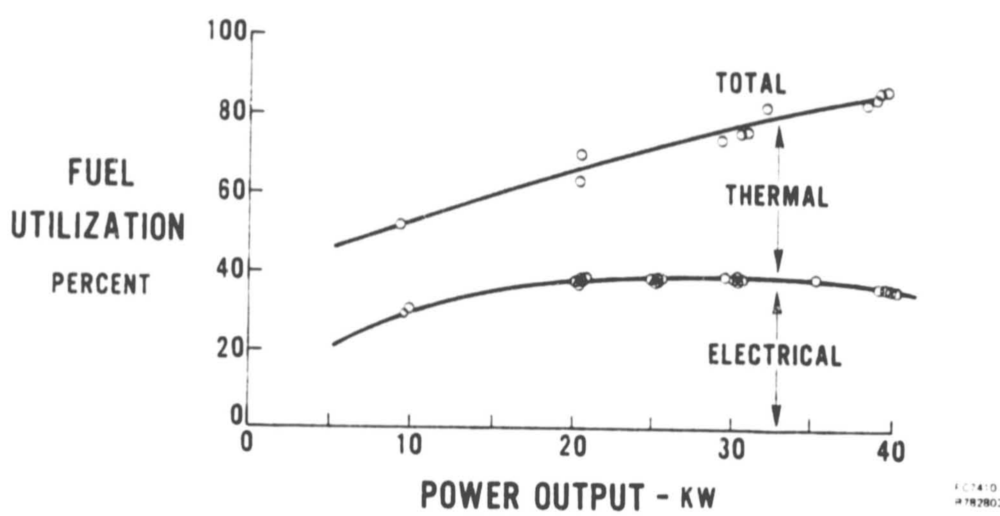
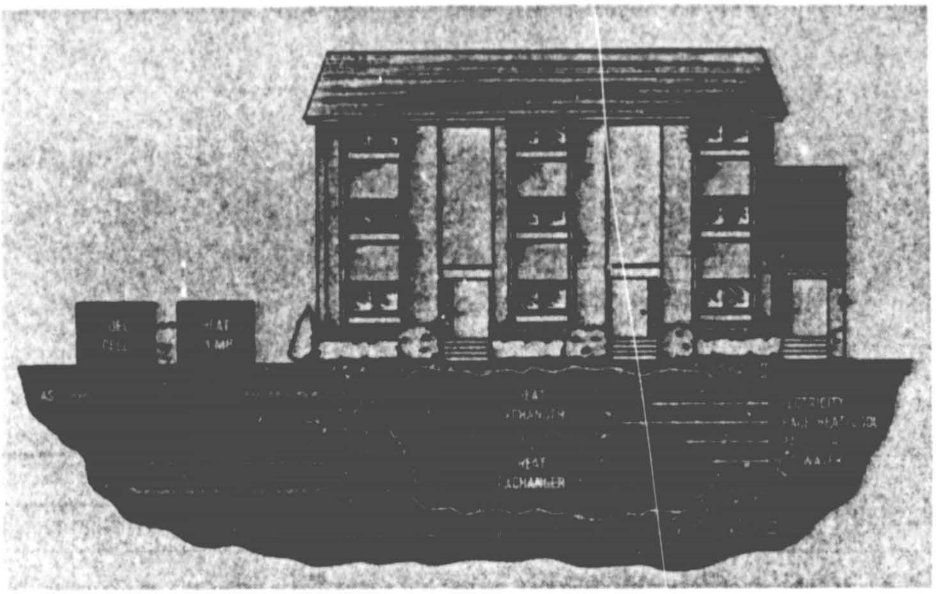


Figure 4. 40-kW Pilot Power Plant Performance



(WCN-7549)

Figure 5. Cogeneration Fuel Cell System

The successful operation of this power plant in United's facility, and continuing gas utility and UTC expenditures and advocacy resulted in a GRI and DOE sponsored $20 million 40-kW development program incorporating recent technologic improvements and customer heat recovery provisions into an improved highly sophisticated 40-kW design suitable for precommercial field test. In August of 1977 the Department of Energy and the Gas Research Institute initiated Phase I of this program to cover design requirements testing and power plant definition, including preliminary design. Phase I was successfully completed and Phase II initiated on 30 June 1978. The Phase I Final Report, FCR-1019, describing the results of the Phase I activities, was issued by Power Systems Division of United Technologies Corporation.

The Phase II program includes the remaining engineering and development effort required to complete the 40-kW power plant improvement. This effort includes engineering analysis and design and component and subsystem testing, and it culminates in the verification testing of a 40-kW power plant of the field test configuration, fabricated in accordance with the new design.

This report covers the Phase II activities completed during the first year, 1 July 1978 through 30 June 1979.

Upon completion of the Phase II improvement program, it is anticipated that DOE will procure approximately 50 power plants for on-site installation test and evaluation by gas utilities and others. Field test will be an important step in building confidence in the overall viability of on-site fuel cell energy systems, and it will be the next major step on the path to full commercialization, Figure 6.

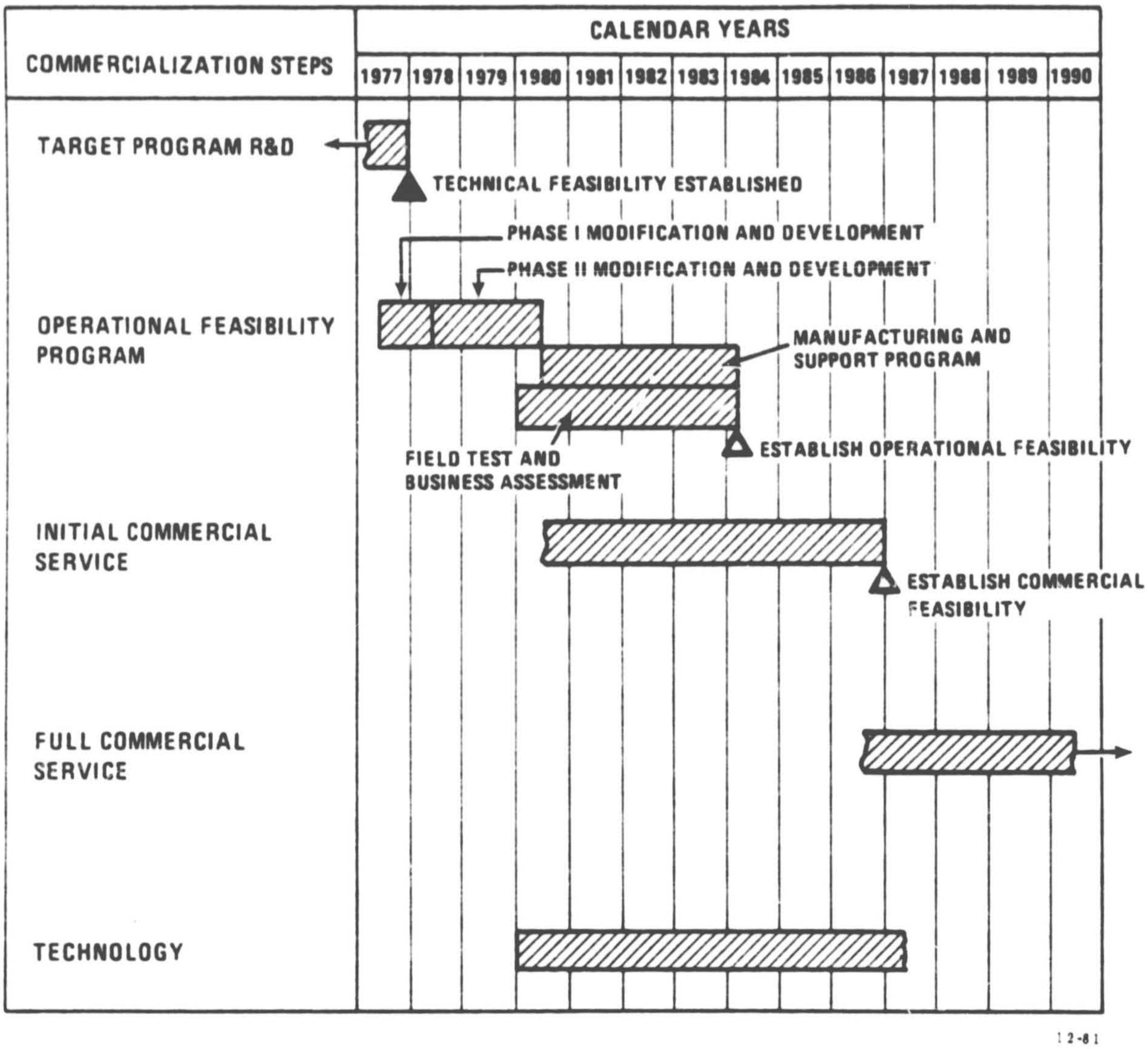


Figure 6. On-Site Fuel Cell Commercialization Path

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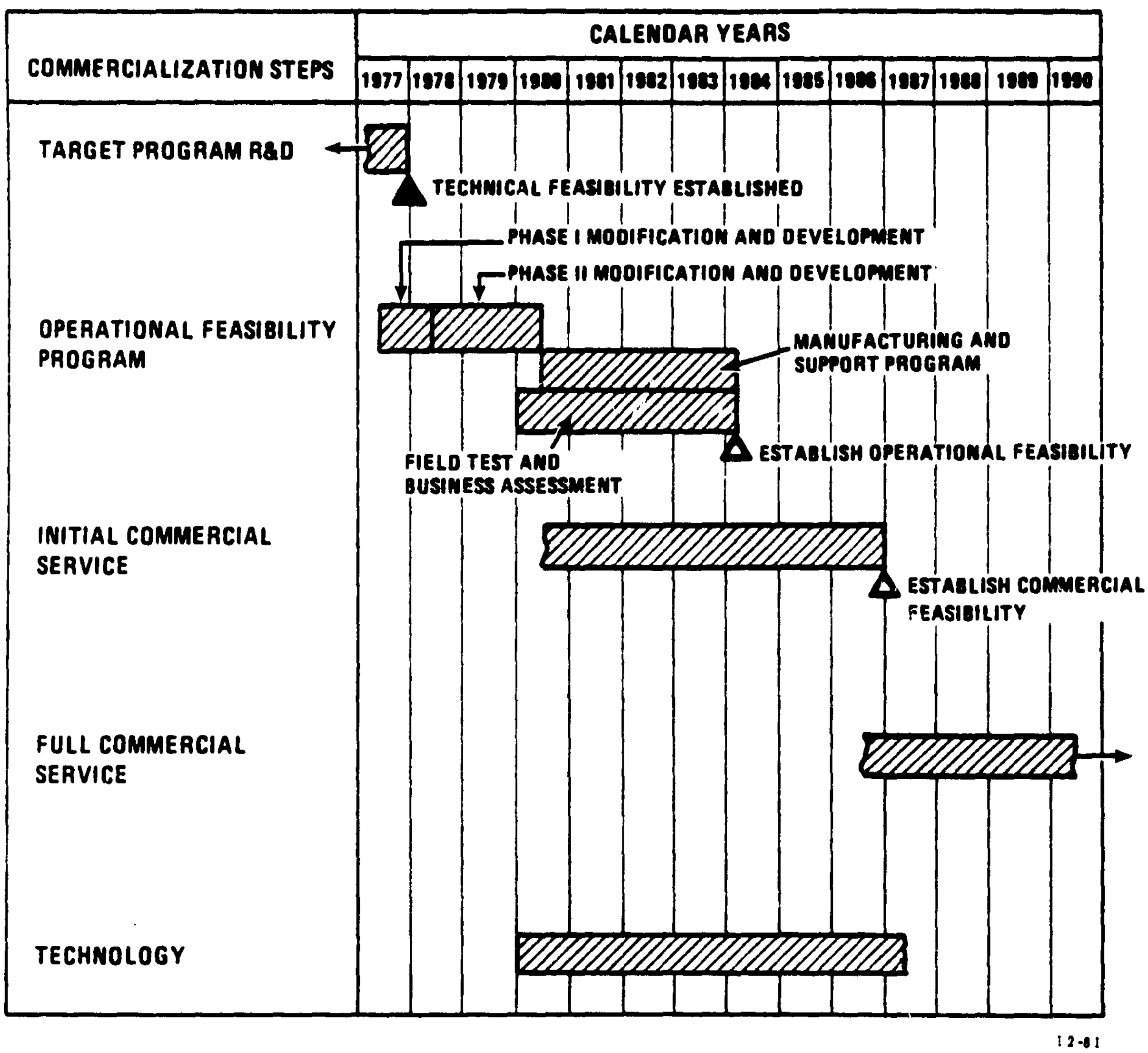

Figure 6. On-Site Fuel Cell Commercialization Path

2.0 OBJECTIVE

The objective of the Phase I program was to initiate design and development actions that would upgrade the pilot 40-kW fuel cell power plant to a configuration suitable for on-site integrated energy system testing in a variety of field applications. These actions consisted primarily of testing to obtain design requirements information and power plant system definition and conceptual design. The improvements will broaden operating capability, increase durability, component life and maintenance interval and lead to reduced production costs.

The objective of the Phase II program was to complete the design, engineering development and verification of the field test 40 kW components, subsystems and power plants, resulting in a precommercial field test configuration satisfying the requirements for on-site installation and service providing both thermal energy at useful temperatures and electricity equivalent or better than conventional power. The new power plant configuration will include the following changes:

Fuel Processing

Changes will be incorporated to broaden the fuel capability to include virtually all pipeline gases and peak shave gases. This requires the addition of preprocessor components to chemically reduce oxygen in peak-shave gas and to reduce unsaturated hydrocarbons such as propylene. The activated charcoal fuel treatment used on the pilot power plant for sulfur removal will be replaced with a hydrodesulfurizer to extend the maintenance cycle. A more active reformer catalyst will be used to increase efficiency and reduce the number of reformer reactor tubes.

Power Section

The latest cell technology will be utilized and the dielectric oil power plant cooling system of the pilot plant will be replaced with a two-phase water system. This improved cooler design will result in a more uniform tempera-

ture distribution power section and improved maintainability. During Phase I, a new cell technology employing a porous ribbed substrate concept was adopted for the baseline cell. This new cell concept offers electrolyte storage believed satisfactory for the goal of five years of continuous operation as well as simplified manufacturing to reduce production quantity cost.

Inverter and Power Plant Control

The inverter is to be modified to improve power plant paralleling capability. For power plant control a microprocessor unit is to replace the electronic controller on the pilot power plant. This will result in reducing controller complexity and size, simplifying field maintenance, and reducing production quantity cost.

Heat Recovery

To allow the power plant to be operated as an integrated total energy system, a waste heat recovery system is to be added to the design. This system will provide heat in the form of hot water.

Power Plant

The power plant is to be repackaged to incorporate customer heat recovery provisions and to improve maintainability.

3.0 CONTRACT TASKS

SUMMARY

Excellent overall progress was made toward the completion of the design, engineering development and verification of improved 40-kW components, subsystems and the power plant. A successful completion of this engineering effort is forecast for May 30, 1980 with a final report to follow on July 31, 1980. Highlights are provided below.

Power Plant Definition

Extensive power plant simulator modeling with "as designed" components and subsystems has confirmed the power plant's capability to meet specification electrical generating efficiency of 40% at 20-kW at 500 hours operating time. The customer side of the high grade heat exchanger has been changed from steam to water at the request of the participating utilities.

Low wattage electric heaters have been added to maintain power section temperatures above 90°F during inoperative periods. Failure Modes and Effects Analysis is 70% complete. The Preliminary Verification Test Plan has been prepared. The 40 kW Model Specification has been revised; however, release will await decision to proceed with power plant weatherization.

Fuel Processor

All elements of fuel processor train have been identified. These include a preoxidizer, a hydrodesulfurizer (HDS), a hydrogenerator, a steam reformer, and a shift converter. The catalyst design volumes for these components have been selected. The reformer/burner verification test program has been completed and the verificiation reformer has met its 20-kW performance goal of 93% conversion at 89% efficiency. Fabrication of the hydrodesulfurizer, shift converter and preoxidizer vessels has been completed. The facilities required to process the shift converter and the hydrodesulfurizer catalysts were designed and fabricated.

Power Section

Design of a 40-kW power section assembly has been completed. Subscale single cell tests for periods up to 8,000 hours were conducted to establish performance stability vs. time and to assess effects of load duty and thermal cycles. Cell catalysts were selected to be NOCAN for the anode and GSA-6 for the cathode. Full scale 24-cell stack assemblies were tested over a range of electrical loads at anticipated power plant conditions to establish the acceptance of the design approaches. A 264-cell power section was assembled and testing begun to evaluate design characteristics. Power section performance goals are being met in both subscale and full scale stack tests.

Inverter

Characterization testing of the inverter breadboards from Westinghouse was completed. Both breadboards were also tested successfully in parallel. Design and component testing of the development (brassboard) inverter and boost regulator power poles have been completed. Verification testing of the microprocessor logic system has been accomplished. The brassboard inverter assembly has been assembled and testing has begun. Long lead time parts and materials for the verification inverter have been ordered.

Controls

Specifications were completed for all control components, including the microprocessor. Specifications were used to solicit candidate control components from vendors. Bench testing of these candidates resulted in the selection of components for the verification power plant. The software for the microcomputer system was written, edited, debugged and run during the testing of the microcomputer.

Thermal Management and Water Treatment

The thermal management subsystem rig was operated to provide information for the design of the thermal and water management component subsystem. Engineering

specifications covering the thermal and water management subsystem were prepared and used to solicit candidate components from vendors. Verification testing of some of these candidates resulted in the selection of the components for the verification power plant. Harrison Radiator Division of General Motors was selected to fabricate all of the heat exchangers except the condensate preheater, which will be fabricated in-house.

Verification Power Plant

The conceptual arrangement of the power plant was established with the help of a hard mockup of the power plant. The mockup includes all major power plant subsystems and components, the plumbing, thermal isolation compartments, and the wiring harness. The power plant has been arranged into three thermally isolated compartments.

The base frame and support structure for the verification power plant has been fabricated. This frame will accommodate all normal handling and shipping loads. Process planning, detail drawings, and quality control requirements for power plant assembly are being defined. Verification test plan activities were started. Design of the power plant test stand was initiated.

Pilot Power Plant Operation

Testing of the pilot 40-kW power plant, originally built and run as part of the TARGET gas industry program, was completed. This power plant has continued to provide performance, durability and other design requirements data needed for optimizing the 40-kW power plant configuration. At the end of the planned testing program, the pilot power plant exceeded 18,000 hours of on-load operation, with over 2800 hours of testing with the latest power section. This total time included a continuous run of over 3000 hours, successful checkout and operation of a microprocessor based electronic control package and repeated demonstration of 38-40% electric generating efficiency and 80% overall fuel utilization.

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.1 Define the Modified Power Plant

> Extensive evaluation of power plant, steady state and transient performance with "as designed" normal and out-of-limits component performance has been conducted with United's power plant simulator model. The results confirm the power plant capability to meet specification electrical efficiency of 40% at 20-kW and to provide an equal amount of energy as heat. Configuration trade and analytical studies were performed in support of detail component design and system simplification. Two new component design requirements (CDR's) were prepared and three existing CDR's were revised. The customer side of the high grade heat exchanger has been changed from steam to water. Low wattage electric heaters have been added to maintain power section temperature above 90°F during inoperative periods. Power plant changes to permit all-weather operation have been defined. The Failure Modes and Effects Analysis is 70% complete. The preliminary Verification Test and Certification Plan has been prepared.

The completion of the Phase I design effort produced a preliminary design concept and detailed design requirements for all power plant components. The primary documents which provided the basis for power plant design analysis, mechanical design, component design and packaging were the power plant process and instrumentation (P&I) diagrams, and the component design requirements (CDR's) which were prepared and issued for all power plant components. A Preliminary Model Specification was coordinated with DOE, GRI and utility representatives and issued.

During this reporting period, power plant components became available either as hardware or as completed designs. These components were evaluated to determine their physical and operating characteristics. These "as designed" characteristics of the components and controls were input to a United power plant simulator model to evaluate steady state and transient performance of the subsystems and the entire power plant under all expected operating conditions. These studies were used to determine acceptability of the hardware and to define any changes or refinements in control schedules, algorithms, and setpoints.

Similar studies were used to determine the impact on power plant performance of individual component degradation or out-of-limits performance. These off-design

studies establish the sensitivity of power plant performance and operability to out-of-limit and failed components. All available component inputs to the power plant simulator deck were completed including updated plumbing heat losses and pressure drops. Power plant performance projections were prepared with these inputs. The results confirmed the specification requirement of 40 percent overall electrical efficiency (lower heating value) at 20 kWac at 500 hours operating time. Efficiency projections and recovered heat projections as a function of ambient temperature and altitude were completed to expand the information available in the 40 kW Power Plant Model Specification.

Configuration trade studies conducted included the integrated HDS/shift converter vessel, integrated heat exchanger studies, preoxidizer inlet condition, process air blower power source, anode exhaust valves, and fuel control tolerance studies. Thermal analysis of the integrated HDS/shift converter vessel configuration using the computer deck indicated that catalyst bed temperatures (HDS, ZnO, hydrogenator and shift converter) were all within acceptable limits at all power conditions. Figures 7 and 8 show the shift converter bed temperature profiles for operation on both natural gas and peak shaved fuels. Maximum temperatures attained are slightly above 500°F with natural gas and about 515°F with peak shaved fuel. In both cases, peak temperatures occur farther down the shift converter bed as power level increases.

Two alternate configurations of the air preheater and the HDS fuel preheater were analyzed to support the integrated heat exchanger studies. The suggested alternates included reversing the position of the two heat exchangers and paralleling the hot side flows. Based on power plant simulations using the computer program, both of these configurations were rejected because of low HDS inlet temperatures at low power levels. Baseline configuration was left unchanged with these two heat exchangers as separate components.

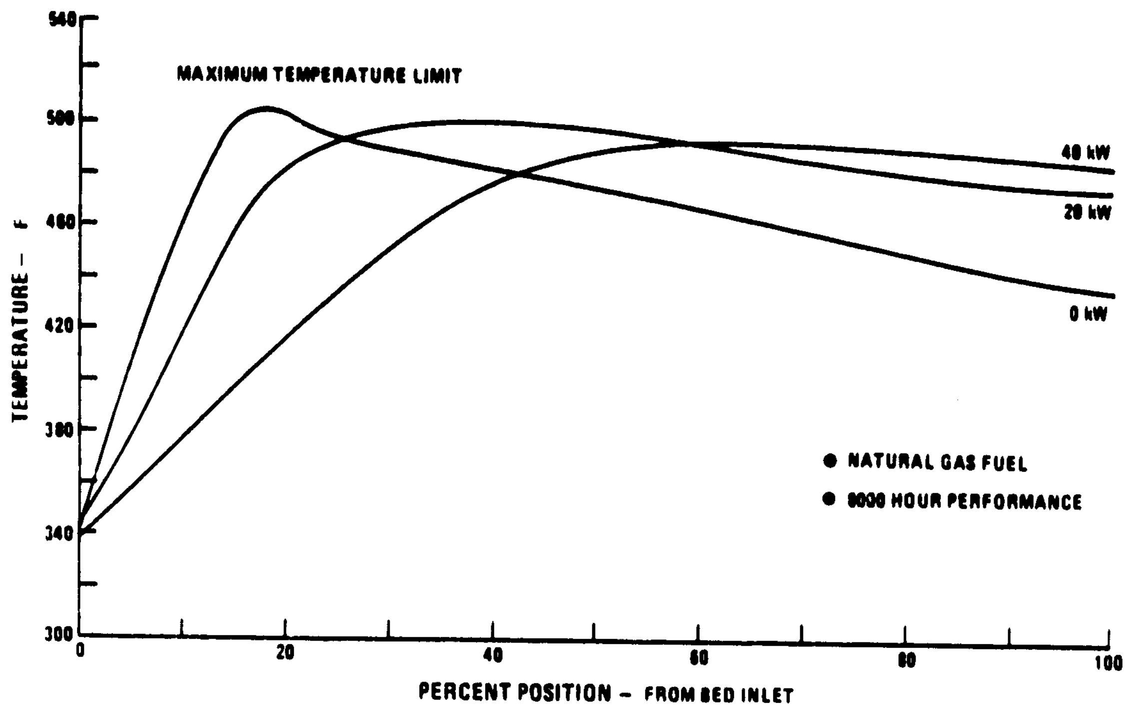

Figure 7. Shift Converter Bed Temperature Profile – Natural Gas Fuel

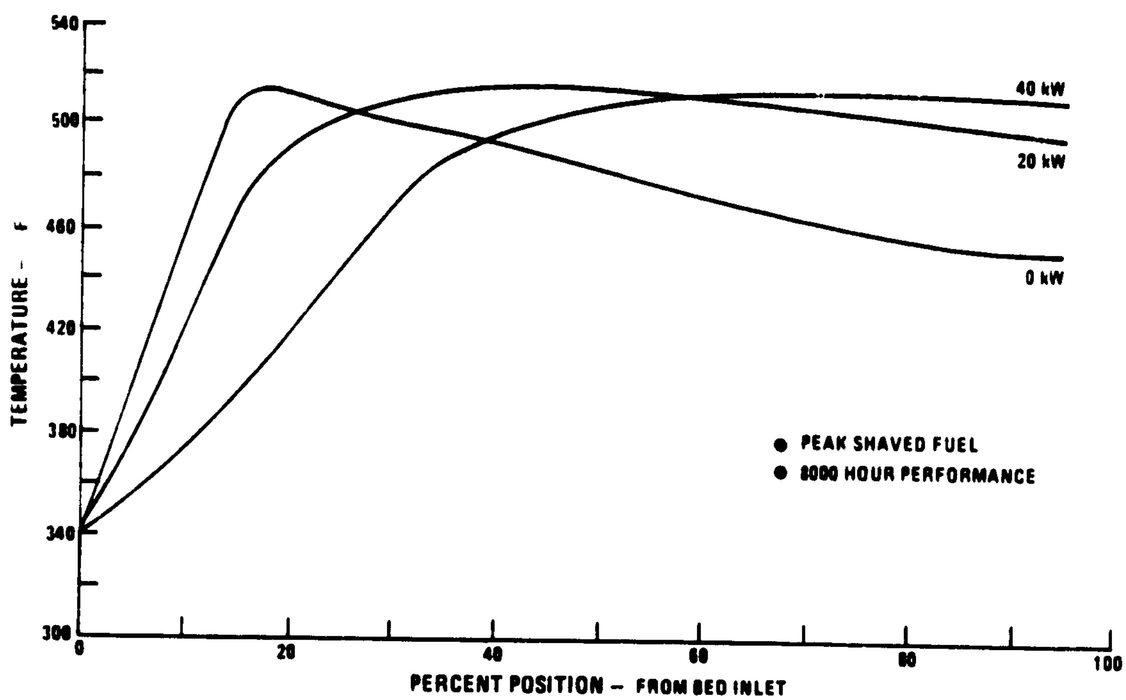

Figure 8. Shift Converter Bed Temperature Profile – Peak Shaved Fuel

Configuration changes at the preoxidizer were required when testing concluded that a preoxidizer inlet temperature of 400°F was required to achieve reliable ignition. This temperature level was achieved by removing the original coolant heated preoxidizer heater and replacing it with a new heat exchanger which used the shift converter exit stream as the hot side. The fuel recycle stream was also relocated to minimize heat exchanger size. The configuration changes described above are shown in Figure 9.

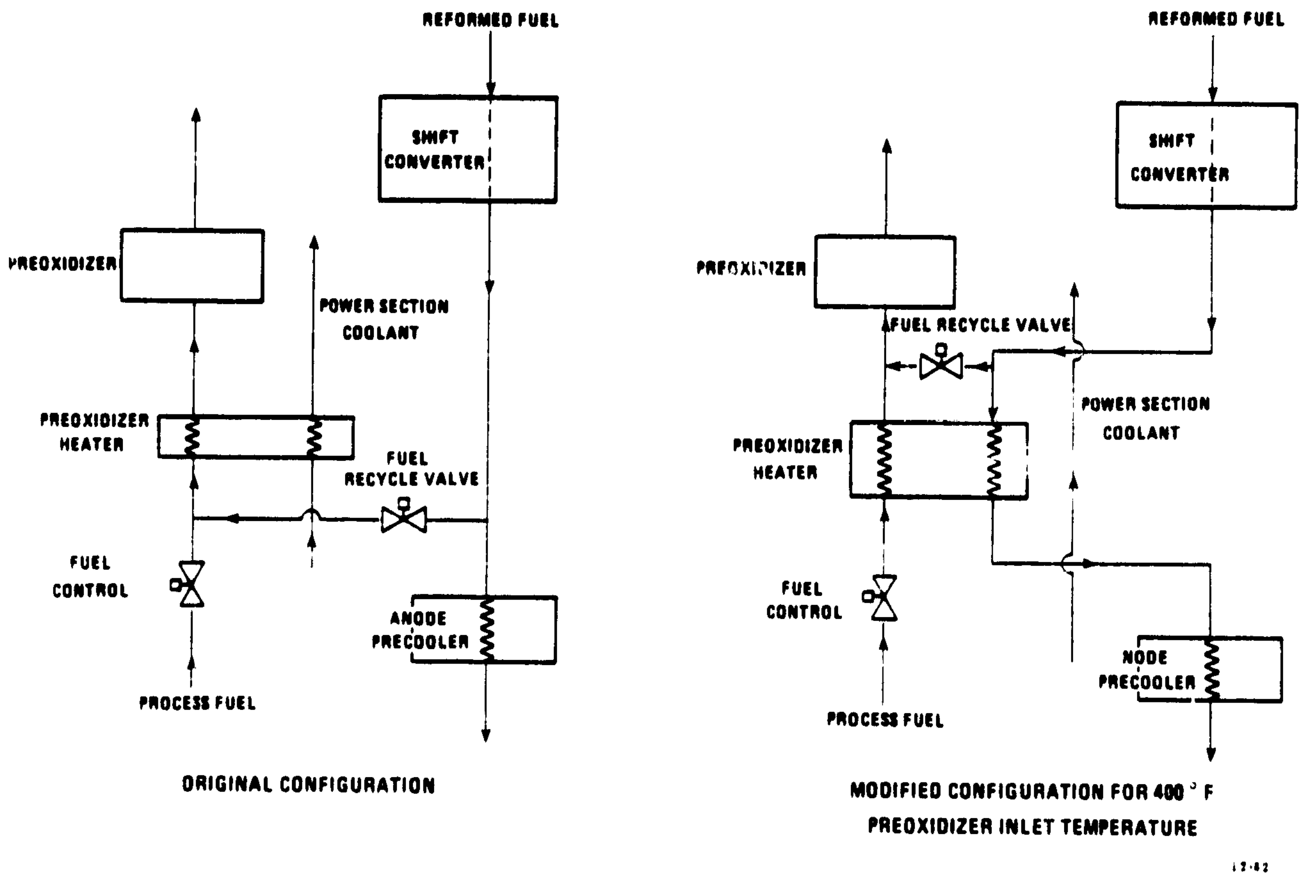

Figure 9. Preoxidizer Inlet Modification

A study of the requirements for the anode exhaust shut off and vent valves concluded that these valves were no longer required. The original function of these valves was to protect the power section from reformer burner combustion product backflow during startup. However, test experience and analysis indicated that both the magnitude of the expected ignition pulses and the cell contamination due

to burner exhaust backflow were within the cell tolerance capabilities. Consequently, the two ball valves were removed from the baseline configuration.

Error analyses of the fuel recycle valve, the fuel active trim valve and the steam control (ejector) indicated that all three of these valves could be operated with a single actuator and drive assembly, simplifying the control. Evaluation of this concept used mechanical tolerances which were examined in worst possible combinations and then compared to the CDR allowable control bands. This single actuation concept was incorporated in the integrated control.

New component design requirements (CDR's) which were prepared during this period included power plant packaging and master control unit (MCU). The power plant packaging CDR provides guidelines for overall dimensions, internal component arrangement, accessibility for maintenance, structural requirements, environment and power plant interfaces. The MCU CDR defines the requirements for the unit which controls the power plant inverters during parallel operation to ensure proper load sharing and shutdown as required. Revised CDR's were prepared for the inverter, the preoxidizer heater heat exchanger, and the high grade heat recovery heat exchanger. Changes to the inverter CDR reflected a reduction in UPS power requirements and the change to AC start power. The preoxidizer heater was modified to reflect the changed hot side stream. A revised CDR for the high grade heat recovery heat exchanger was issued after DOE and GRI approved the change from steam to water. Design flow conditions on the customer side were changed to 80°F water in and 160°F water out. The water exit temperature can be raised as high as 275°F with proper adjustment of customer side flow rate, inlet temperature, and water pressure. The total quantity of recovered heat remains unchanged with this revised heat exchanger.

Conceptual definition studies were conducted to define the power plant modifications necessary to allow cold weather/all-weather operation. The scope of these studies was to define the changes required to permit operation in -25°F to +120°F ambient without a separate shelter. The recommended changes to the power plant include enclosing the inverter logic components in an insulated compartment; adding controls to reduce inverter cooling air flow at low ambient temperatures; elimi-

nating induced air flow through the condenser; ducting process air from ambient to the blower inlet, and modifying cooling provisions for the water treatment subsystem and feedwater cooler. These weatherization studies were completed as input for DOE/GRI discussion covering possible power plant design changes.

The results of the electrolyte freeze test program produced recommendations that new power sections be conditioned on shutdown for transportation and thereafter to keep the power section warm. Keeping the power section warm reduces shutdown losses to unmeasurable levels. A conceptual design study was conducted to determine the changes necessary for the stack heating approach. The resulting configuration uses 420 watts of silicone rubber heater sheets positioned externally on the stack reactant plenum with thermostatic control to maintain a cell temperature of 90°F to 130°F under all ambient conditions.

Verification power plant documents completed during the reporting period included the Verification Test Plan outline and draft and the instrumentation and diagnostic requirements for the verification power plant. The latter identifies the temperature, pressure and flow measurements that will be taken during testing and used to establish the component and power plant characteristics required to verify the design.

Cost estimating activities included volume production cost projections for review with DOE and their consultants. Process planning activities were completed for the cell stack assembly and for the controls areas. CDR cost goals were allocated to components for production levels of 50 and 10,000 power plants per year. The allocation was based on power plant manufacturing recurring cost estimates of $1500/kW at the 50 units per year rate and $250/kW at the 10,000 units per year rate.

Failure Mode and Effect Analyses (FMEA) were approximately 70% completed during this period. For these analyses the power plant components were divided into functional subsystems. Areas completed included the fuel processing subsystems, air processing subsystems, flow control valves, thermal management, water recovery,

and water treatment subsystems. The major areas remaining were the power section, controls, and inverter. Review of the reformer start burner system was completed. Burner shutdown and startup sequencing and timing satisfy or exceed the requirements of UL-795 and ANSI Z21.17. From a survey of state, county, and city requirements pertaining to pressure vessels, it was determined that the 40 kW power plant will not be subject to any law or ordinance that requires a stationary engineer for steam generators. However, the survey revealed that ASME vessel certification would be a legal requirement in several localities. Certification will be sought at an appropriate point in the design process.

The American Gas Association Laboratory was contacted as a possible testing laboratory that could review the power plant design guidelines to assure conformance with portions of material standards applicable to the power plant. AGA Laboratories was visited to discuss the possibility of having AGA test the 40 kW power plant and to eventually conduct a certification program of the production design. Discussions with AGA will continue in order to define actions that might assist power plant sitings and approval by code officials.

The 40-kW Model Specification was prepared, but not released, pending clarification of possible changes resulting from power plant weatherizing.

The 40-kW power plant functional schematic diagram was updated and is shown in Figure 10.

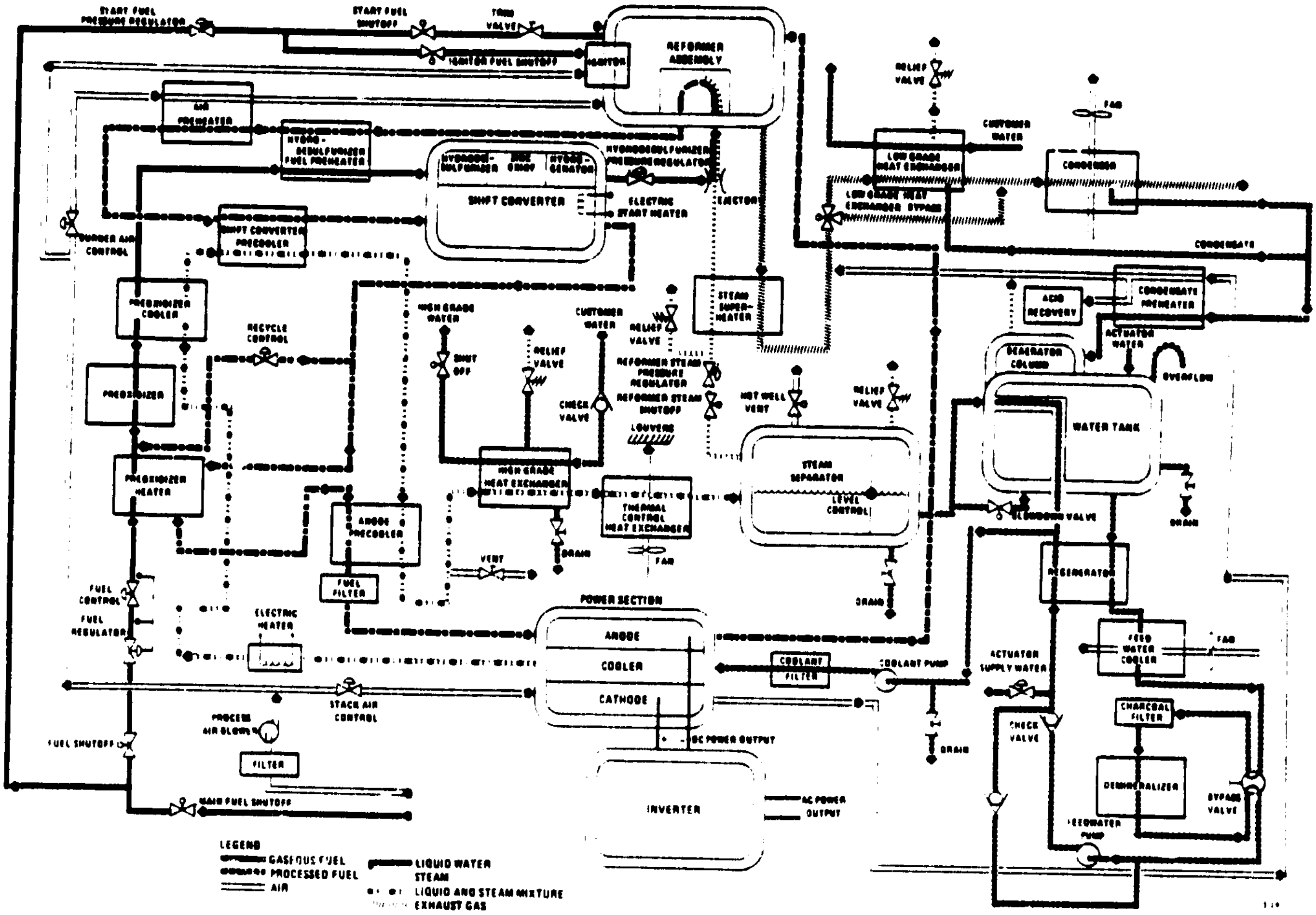

Figure 10. 40 kW On-Site Power Plant Schematic

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Design Verification of the Power Plant

Subtask 1.2.1 Fuel Processor Subsystem

> All elements of the fuel processor train were designed. These include a preoxidizer, a hydrosulfurizer, a hydrogenator, a steam reformer, and a shift converter. The reformer/burner verification test program has been completed and the verification reformer has met its 20 kW performance goal of 93% conversion at 89% efficiency. Fabrication of the hydrosulfurizer, shift converter and preoxidizer vessels has been completed.

The Phase II fuel processor design and development objectives included expanding fuel capability to handle pipeline gases, extending the maintenance cycle to 8,000 hours, completion of the design and the verification of the design by computer models and testing of component and the subsystem.

Specific activities completed are:

- o Updated fuel processor component design requirements (CDR's).
- o Completed preparation of detailed engineering drawings and specifications for fuel treatment and fuel processing components. Performance was verified with a design computer model.
- o Completed reformer/burner verification test program to confirm component design requirements.
- o Defined hydrosulfurizer, preoxidizer, and shift converter catalyst operating conditions and catalyst.

Fuel Preprocessor Activities

A schematic for the fuel processing train is shown in Figure 11 with the final catalyst design volumes. The final design for the fuel preprocessor has been completed. The preprocessor serves to remove contaminants in the fuel prior to processing in the reformer and shift converter catalyst beds. The preprocessor consists of an adiabatic preoxidizer, a hydrodesulfurizer, a sulfur absorber and a hydrogenator. The preprocessor components operate at subatmospheric pressure.

The preoxidizer removes oxygen in propane-air peak-shaving gas by catalytic combustion with recycled hydrogen from the process gas stream. The hydrodesulfurizer converts organic sulfur compounds in the gas to hydrogen sulfide which is absorbed in the zinc oxide bed. The hydrogenator reduces propylene in the peak-shaving feed gas to avoid coking in the reformer.

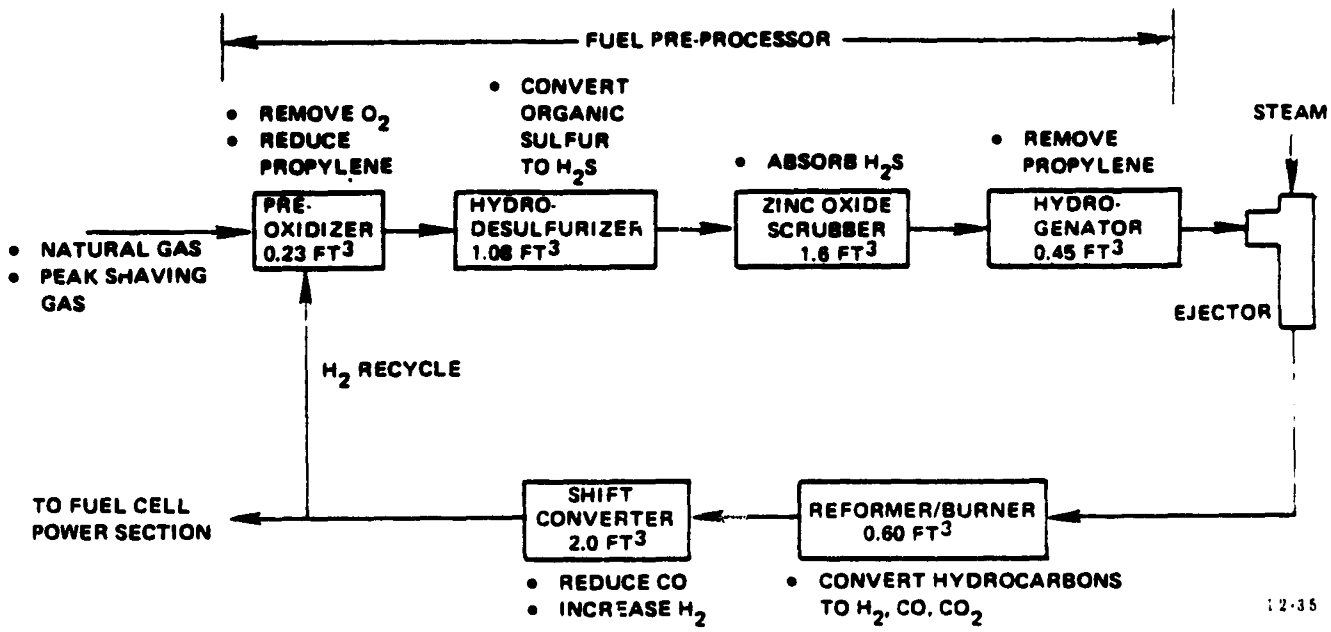

Figure 11. 40-kW Fuel Processing System

Preoxidizer

Subscale testing of the preoxidizer showed that the limiting criterion is reactor start-up after the catalyst has become sulfur poisoned during long periods of non-peak shaving operation (i.e., summer). Based upon the start-up requirement, a 0.23 ft^3 bed volume (20 lbs. of catalyst) was required. As shown in Figure 12, a 20 lb. preoxidizer with over 200 hours of "worst case" stabilitv testing at maximum temperatures would slip a maximum of 0.5% O_2. This oxygen slippage will cause no permanent damage to downstream HDS, ZnO, and hydrogenator catalysts.

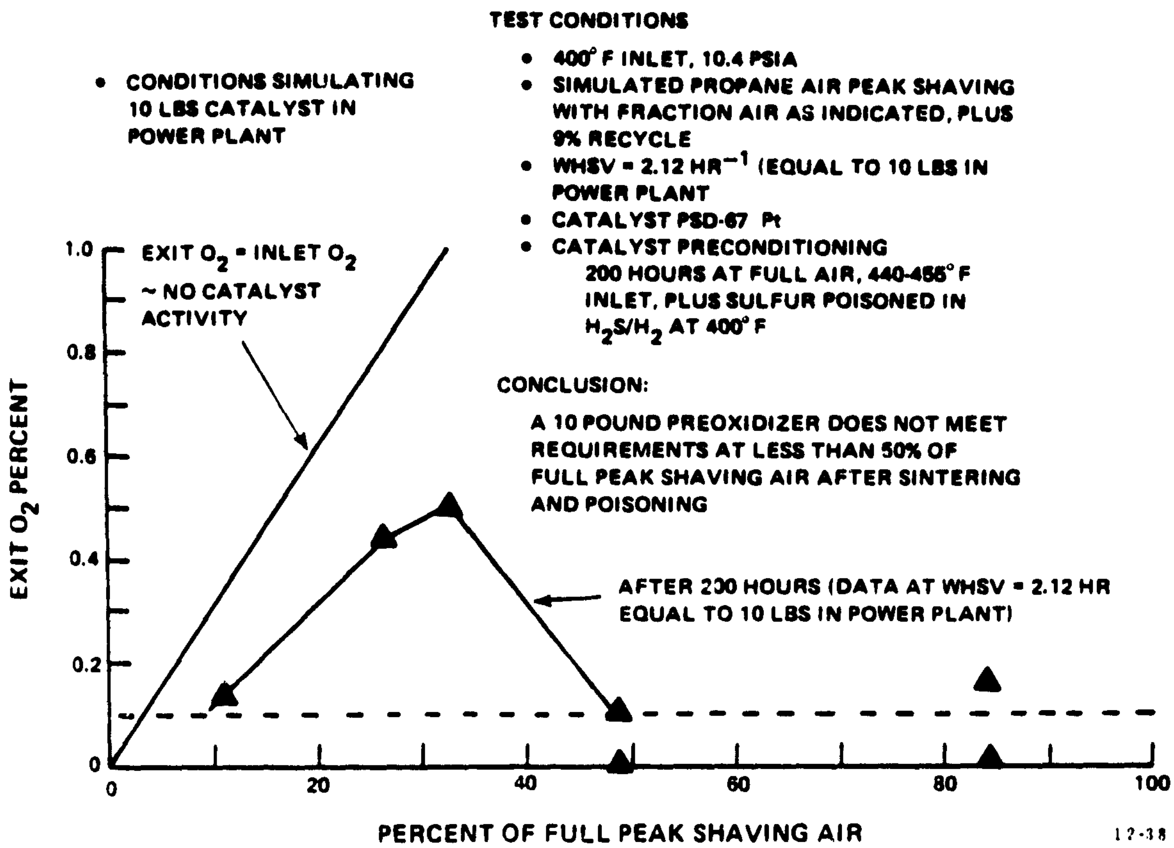

Figure 12. 40-kW Preoxidizer Ignition Test Results After 200 Hours Stability Testing

Hydrodesulfurizer

Fabrication of the hydrodesulfurizer (HDS) shift converter and preoxidizer vessels was completed by the PSD shop. All of the vessels have been pressure tested and cleaned, and are currently being inspected. The HDS catalyst requires controlled conditioning prior to use. The catalyst will be conditioned in bulk and transferred to HDS reactor under a nitrogen atmosphere. The design of the hydrogenator is based on reducing propylene content of the gas entering the reformer to 0.15%. This is accomplished by recycling power section anode gas containing hydrogen, in the presence of a catalyst.

Two high-activity hydrogenator catalysts containing palladium were tested and found to have unacceptably high decay rates. A platinum catalyst selected for this use demonstrated excellent stability after 450 hours of endurance and shut-

down testing, Figure 13. The power plant hydrogenator was sized at 0.45 ft³ for 16,000 hours, based on performance data obtained during the stability test, Figure 14.

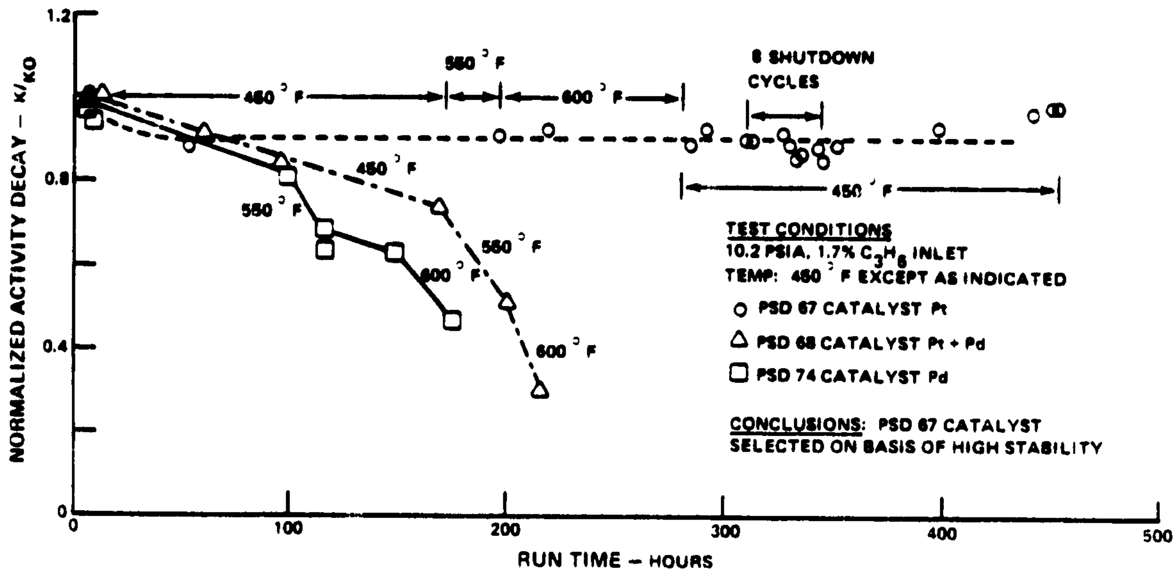

Figure 13. 40-kW Onsite Hydrogenator Testing Stability Test Results

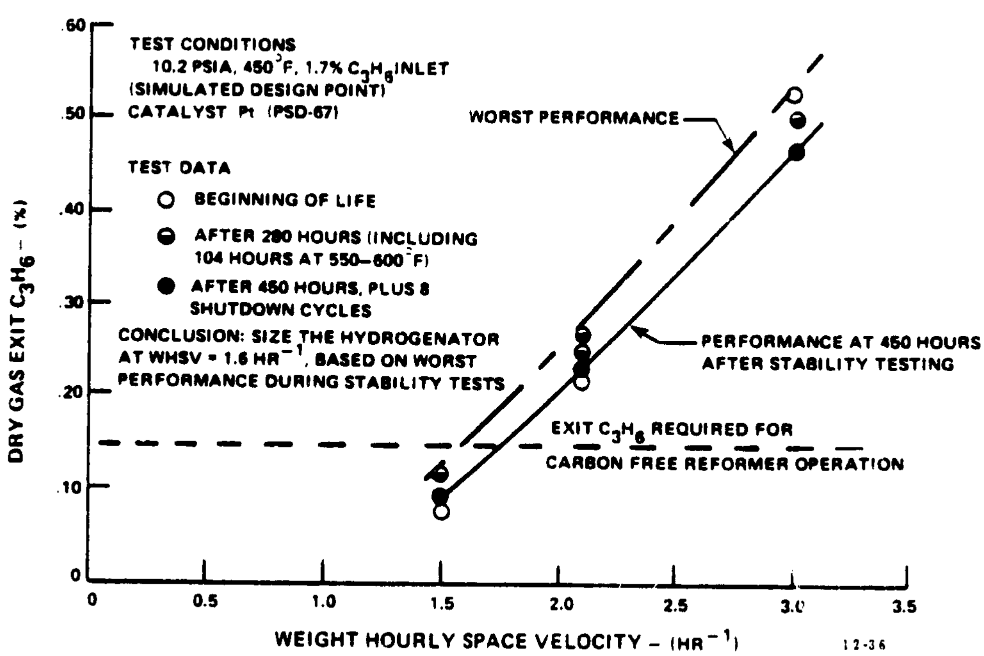

Figure 14. 40-kW Onsite Hydrogenator Testing Exit Propylene Vs. Space Velocity

Reformer and Shift Converter

Design of the reformer and shift converter were essentially completed during the first annual reporting period. Reformer testing is discussed later in this report. The catalyst for the shift converter will be conditioned at pressure for which the vessel was not designed (because of cost). This catalyst will be loaded into the vessel which is installed in a test fixture to ensure pressure balance across the reactor walls during the conditioning process.

Process Fuel Filter

A preliminary design for a process fuel filter (Figure 15) using a PSD housing and a vendor's standard filter tubes is in process. This filter is to collect the copper fines from the shift converter bed.

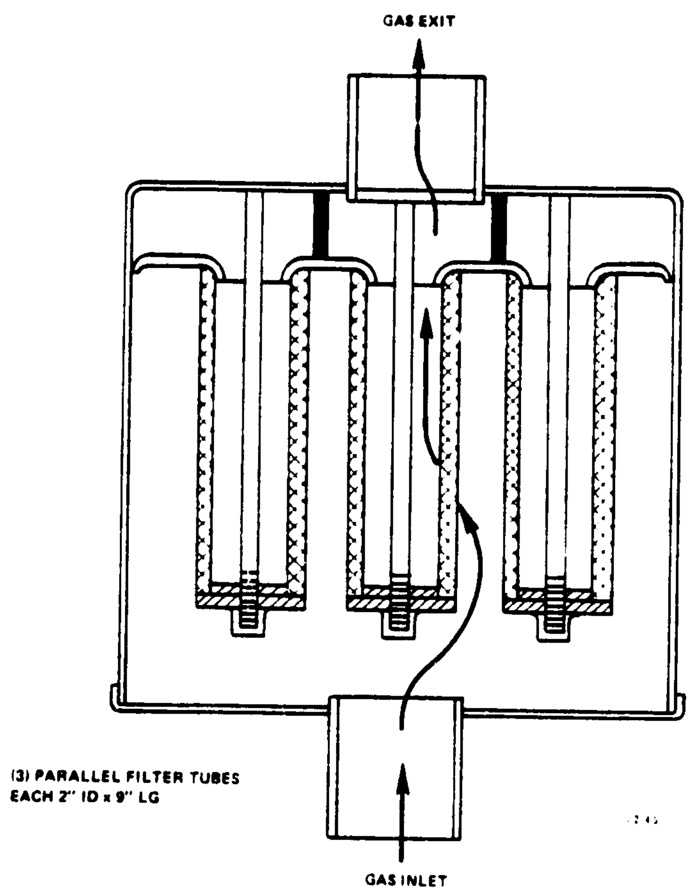

Figure 15. Process Fuel Filter FIL-204

Fuel Processor Component Test Facilities

An existing test stand has been reconditioned for fuel processor component preconditioning The facilities requirements needed to process the shift converter and the hydrodesulfurizer catalysts were established. Construction of the shift converter catalyst reduction work station was completed, Figure 16, and the reduction of catalyst was initiated. Construction of the hydrodesulfurizer catalyst presulfiding work station was completed, Figure 17, and system checkout initiated.

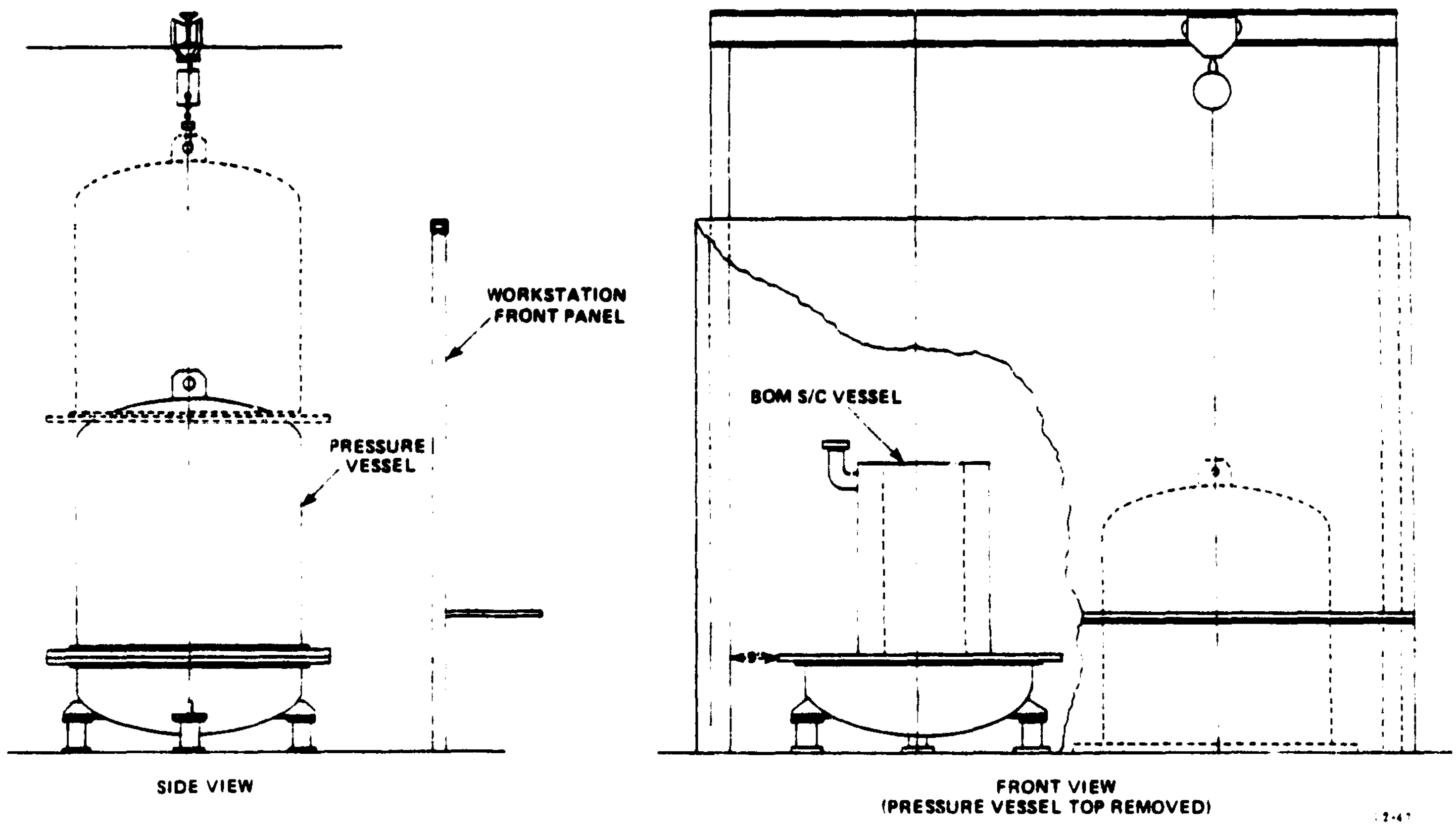

Figure 16. Preliminary 40-kW S/C Catalyst Reduction Workstation Layout

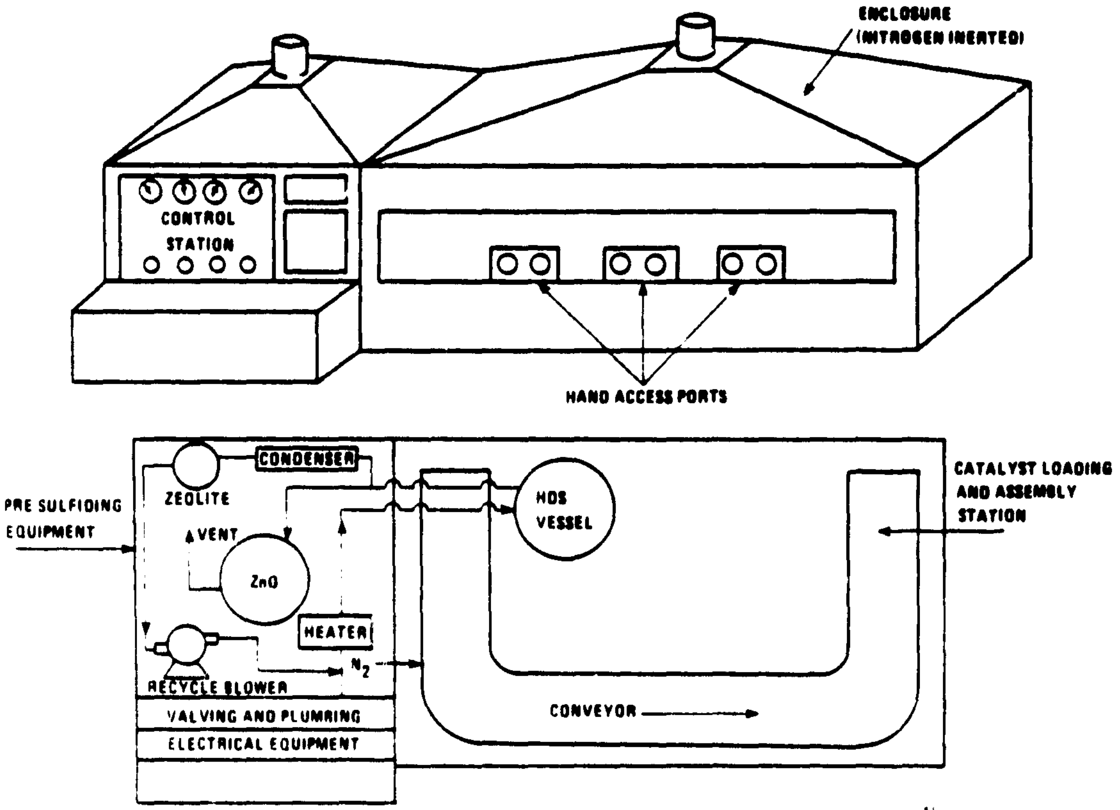

Figure 17. Preliminary 40-kW HDS Workstation Layout

Reformer/Burner Verification Test

The reformer/burner verification test program was completed, Figure 18. The reformer met its CDR performance goal of 93% conversion at 89% efficiency at 20-kW. Performance at 30-kW and 40-kW simulated operating conditions was measured to further define the operating characteristics. Testing revealed that the actual control temperature change with increasing power was larger than that predicted. Computer matching studies are in process to simulate these test results and to redefine the reformer tube control temperature schedule, if required. Should these studies indicate a need for a new schedule, some additional test points may be required. Simulated peak-shaving gas test points were also completed. Data is presently being reduced and no problems have arisen to date. Simulated up transients from "0 net" power to "40-kW" loads with fuel and air overflow and downtransients from "40-kW" to "0 net" power were successfully completed.

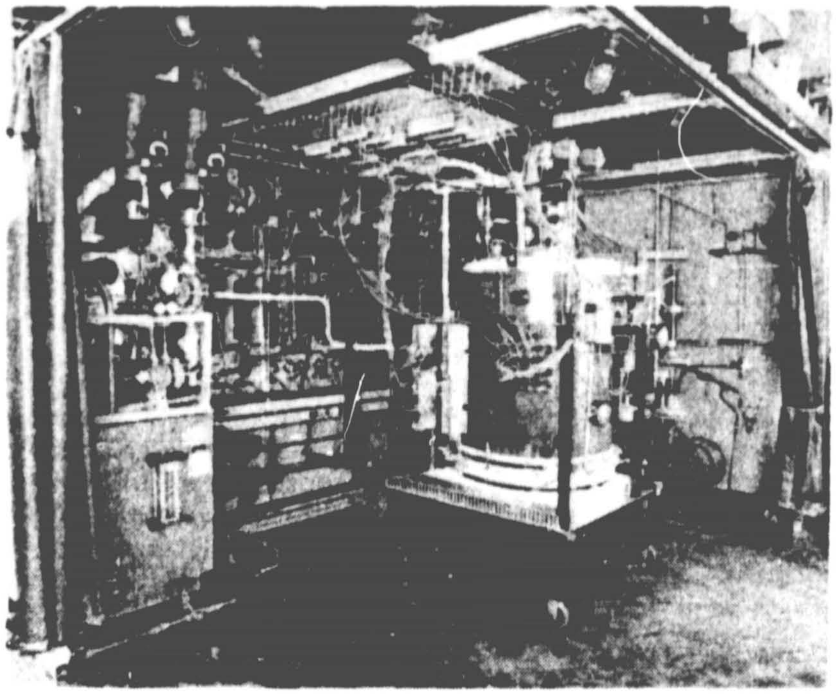

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Figure 18. Reformer/Burner Assembly

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Verification of the Power Plant

Subtask 1.2.2 Power Section

Design of a 40-kW power section assembly was completed. Subscale single cell tests for periods up to 8,000 hours were conducted to establish performance stability vs. time and to assess effects of load duty and thermal cycles. Cell catalysts were selected for the anode and cathode. Full scale 24-cell stack assemblies were tested over a range of electrical loads at anticipated power plant conditions to establish the acceptance of the design approaches. A 264-cell power section was assembled and testing begun to evaluate design characteristics, Figure 19. Power section performance goals are being met in both subscale and full scale stack tests, Figure 20.

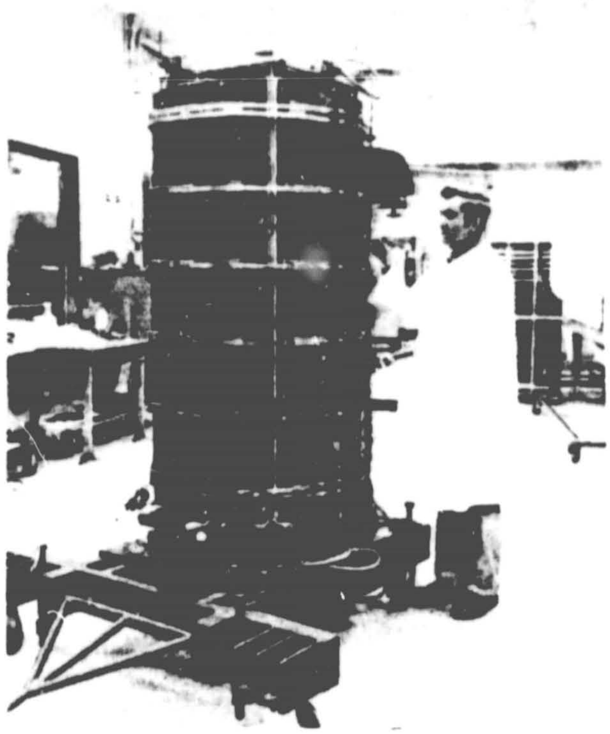

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Figure 19. 264-Cell Power Section Cell Stacks

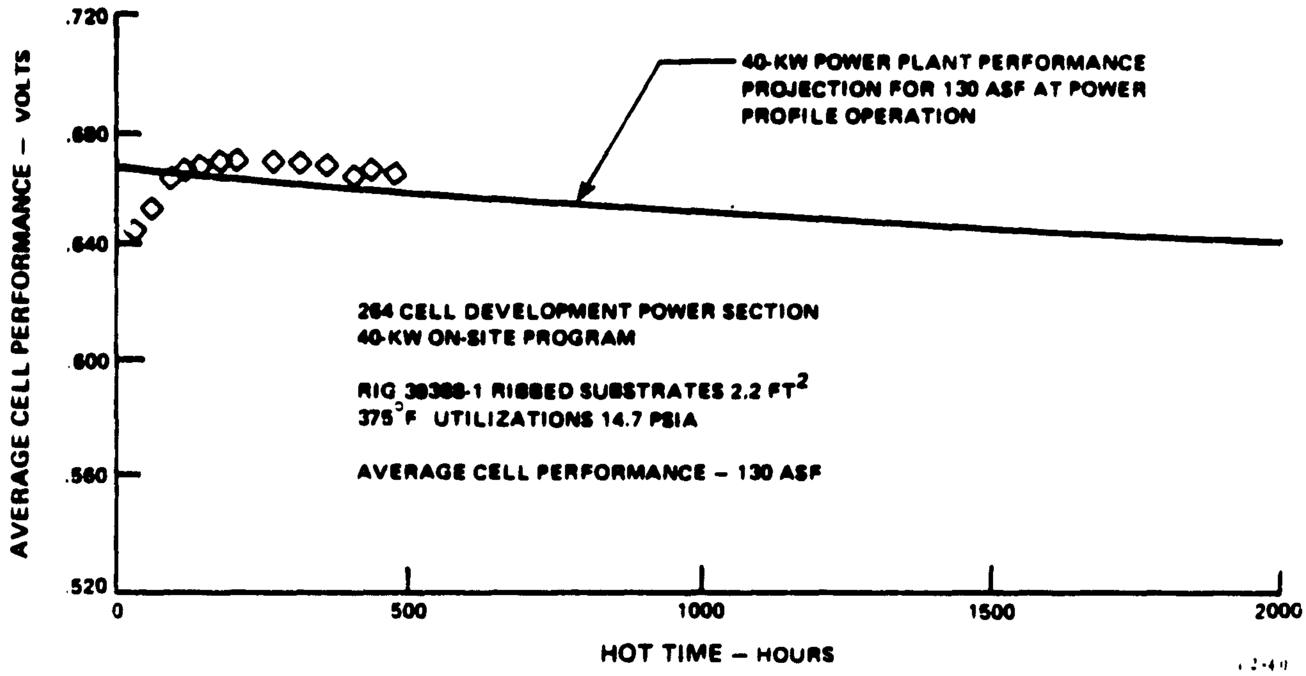

Figure 20. 264-Cell Development Power Section Performance Log

The objectives of this reporting period included design activities and single cell and multi cell performance verification tests to confirm that the established design requirements are being met. Specific goals included:

- Updating the power section component design requirements (CDRs).
- Preparation of detailed engineering drawings and specifications for the power section and verification of performance with a computer model.
- Complete testing of sub-scale single cells to determine that the component design requirements are met.
- Testing of full scale 24-cell assemblies to verify cell manufacturing techniques and multi-cell operation at simulated power plant conditions.
- Fabrication of the full scale development power section and initiation of testing to verify that design requirements are met.

Power Section Design Activities

Numerous power section design activities were conducted during this reporting period in order to firm up the power section design:

- o Completion of the design of the steam manifold penetration through the fuel manifold. The coolant assembly penetrates the top of the fuel manifold, using the flange and a gasket for attachment and sealing.

  This configuration satisfies earlier concerns with cost, ease of assembly and both pressure drop and stability of the two-phase flow through the exit elbow.

- o A Teflon (TFE) seal frame was designed to provide a tough dielectric envelope around the sealing lip of all reactant manifolds. This will provide satisfactory electrical insulating characteristics between the stack and the manifold seal perimeter and resistance to shipping and handling damage. Forming and bonding trials being conducted under DOE technology, contract DE-AC-03-76-ET11301, have supported this design.

- o The reactant manifold retention strap brackets were lengthened to accommodate more spring washers anticipated to be required.

- o Air inlet and exhaust distribution baffles were made separable from their respective manifolds to allow access for coating and for development flexibility.

- o Definition of cell stack assembly (CSA) instrumentation for both development and delivery power plants was completed.

- o The cell stack assembly layout for initial development parts was completed.

- o Updating of the stack characteristics (pressure, drop, volumes, etc.) for use in United's computer program was completed. Calculated coolant pressure drop for rated power and start-up conditions is shown in Figure 21. The large band for rated power is due to uncertainty in liquid hold-up in the exit manifold with two-phase flow. However, as long as ΔP is within this band, flow distribution should be adequate for operation down to less than half the design flow rate of 1800 lb/hr.

- o Design of a fibrous cooler holder and a revised cooler was completed. This revision incorporated the latest cooler tube spacing as determined by rig temperature probing and heat transfer analysis.

- o As a result of the recent design changes, power section reactant pressure drops were recalculated. Figure 22 shows the air and fuel pressure drops. The air side ΔP is below the CDR limit by 8%; the fuel side is over by 5%. The 5% excess fuel ΔP is only .04% of the overall power plant pressure drop and will cause no problems in power plant operation or efficiency.

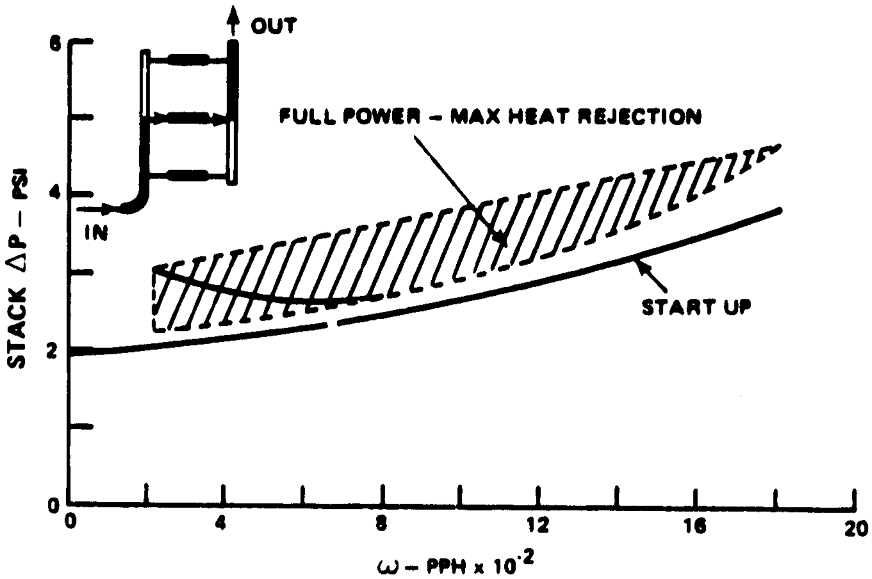

Figure 21.
40-kW Stack Coolant ΔP vs. Flow

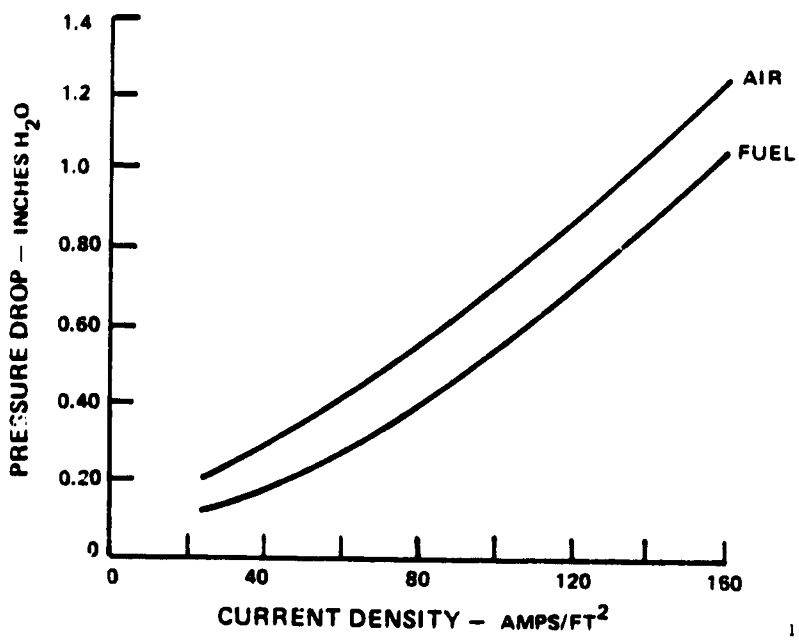

Figure 22.
40-kW Power Plant Reactant ΔP

- New cell edge wet seals were incorporated into the electrode design. Structural analysis of this cell package indicates that stresses are within allowable limits with no changes in compressive load or seal thickness from the edge seal used previously. A slight increase in seal width was required because of strength limitations in the transition area.

- o A power section design review was held, and several items requiring continued development input were identified. The coolant manifolds were redesigned to improve reliability of the cooler connector-to-manifold braze joint after marginal engagement of these parts was evident from manufacturing trials. Test data from the first full scale development power section is needed to verify coolant exit manifold size. Detailing of the revisions to improve cooler array temperature profile based on 24-cell stack testing is nearly complete. These changes will be verified by additional tests. Stack mounting hardware is being revised to enhance accessibility of the installed stack.

- o The study to determine a suitable method of protecting the power section against electrolyte freezing was completed. The approach chosen for evaluation consists of four silicon rubber embedded resistance heaters bonded to each plenum to maintain stack temperatures above 90°F. The heaters will be controlled by a thermal switch on the stack assembly. Electrolyte freeze protection during initial shipment to installation site when power is presumably unavailable will be handled by water dilution of electrolyte to a condition where it will not solidify. The design for this heater arrangement has been started.

Subscale Cell Testing

The remaining two of the original seven 2" x 2" cells completed their 8000 hour programs. Both cells contained ribbed substrates. In both cells, the majority of iR increase was attributed to rig connected corrosion of the gasket between the carbon and stainless steel plates. This corroding component is not present in full scale cells. The control cell, 3245, at 600 mV, ended testing on the 40-kW projection for steady 300 ASF endurance operation, Figure 23. Of the total loss throughout 8000 hours, the major mode of decay was H_2-O_2 performance all of which was cathode catalyst activity decline. The remaining decay was split equally among increases in iR, O_2 gain and H_2 gain.

Build 3244, the load profile cell, completed its program attaining the 8000 hour 40-kW load profile goal, when corrected for iR losses due to gasket corrosion. Of its total performance loss, the majority was again an H_2-O_2 performance decay, the rest being a 19 mV increase in O_2 gain, a 16 mV increase in H_2 gain, and a 7 mV increase in cell iR. The major difference between 3244 and 3245 was higher cathode diffusion losses in 3244, a result of corrosion of the carbon that supports the catalyst, and change in wetting angle caused by higher cathode potentials.

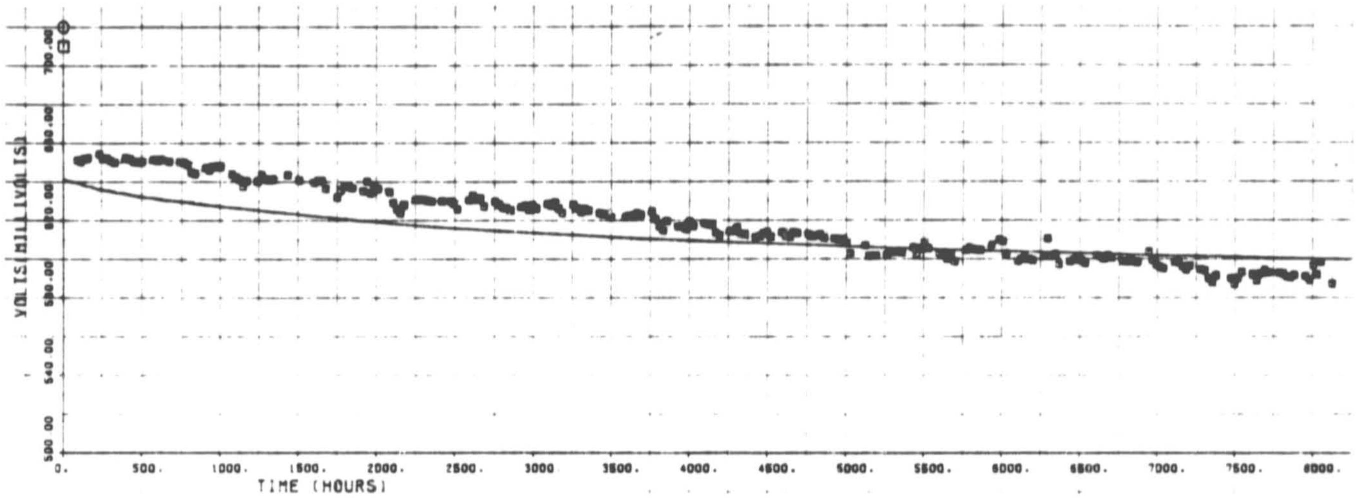

Figure 23. Performance of 2 x 2 Inch Cells Relative to 40-kW Power Plant Goal

Eight new 2" x 2" cells were started on the endurance bench to measure the effect on performance and stability of load cycling for proposed 40-kW electrodes. All cells were fabricated from anodes with an added treatment for preservation of wettability and paired with one of the following four cathode catalyst layers on ribbed substrates using production procedures except were noted.

1. GSA-7 - Builds 3307, 3308.
2. AMCAN - Builds 3309, 3310.
3. GSA-6 - Builds 3311, 3312.
4. GSB-1 - Builds 3313, 3314.

Builds 3313 and 3314 (with GSB-1 cathodes and NOCAN$_{TM}$ anodes on ribbed substrates) were removed from test after 1100 hours. These two cells had large anode gas diffusion losses, cathode catalyst activity losses, internal cathode catalyst layer diffusion resistance losses and iR increases which caused cell performance losses of 101 and 84 mV, respectively.

The remaining six 2" x 2" cells (Builds 3307-3312) exceeded 7000 hours of testing with most of the operating time being accumulated at high potential (daily cycles between 28 ASF and 71 ASF). The cells using GSA-6 type cathodes continue to meet performance goals. One AMCAN$_{TM}$ cathode cell and both GSA-7 type cathodes

failed to meet the 6000 hour performance goals. Performance problems with the GSA-7 cells are primarily increased cathode diffusior losses. The poor $AMCAN_{TM}$ cell has high anode diffusion losses and less stable cathode catalyst activity. All diagnostic parameters for the GSA-6 cells are within expectations. The increase in cathode diffusion losses is half that of the other cells, and the stability of H_2-O_2 performance is better than that for the $AMCAN_{TM}$ cell indicating that the benefits of the GSA carbon catalyst support are being realized. The 200 ASF check points compared with goal performance are shown in the table below:

TABLE 1. LOAD PROFILE DATA TO 7000 HOURS AT 200 ASF CONDITIONS

		Performance*		
Build	Cathode	Beginning of Life	7000 Hours	Decay
3307	GSA-7	617 mV	575 mV	42 mV
3308	GSA-7	612	575	37
3309	$AMCAN_{TM}$	629	569	60
3310	$AMCAN_{TM}$	640	600	40
3311	GSA-6	632	604	28
3312	GSA-6	627	593	34
Goal for Cells at Load Profile		641	579	62

*Corrected for increase in Cell iR caused by gaskets.

These subscale cell results supported by experience in a 24-cell stack of 2.2 ft^2 cells led to the selection of GSA-6 for the full scale development power sections.

Full Scale Short Stack Testing

Testing of the first Proto 1, 24-cell stack of 2.2 ft^2 square ribbed substrate cells shown in Figure 24 was completed following the attainment of all planned test goals with the following results:

- o Demonstration of satisfactory thermal control with coolers at six-cell intervals. (This represents a cost reduction from five-cell intervals in earlier programs.)

- o Design information needed for selection of power plant cathode exhaust (acid) scrubber and condensate preheater.
- o Demonstration of locked-up stack concept up to simulated operating times beyond 40,000 hours.

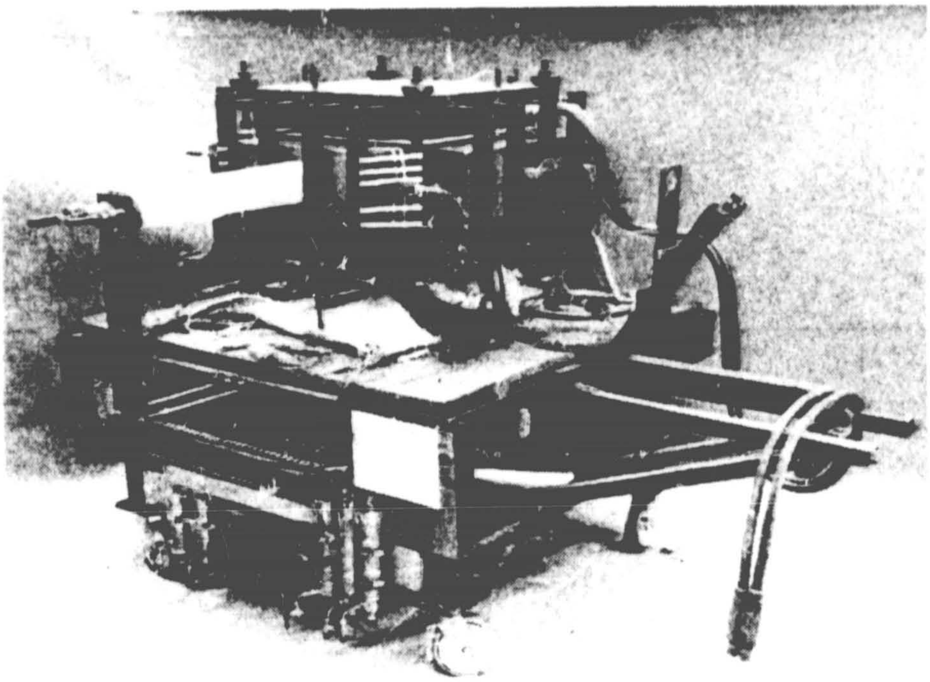

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Figure 24. 24-Cell Stack of 2.2 Ft Square Cells

A total of 4250 hours of load operation, including 21 thermal cycles was accumulated over a range of electrical loads at anticipated power plant conditions. The performance and run history are shown in Figure 25. During the assembly process, half of the cells contained anode and cathode electrolyte reservoirs filled to 40% of the geometric capacity. Preliminary estimates indicated filling to that level will meet the power plant objective of 40,000 hours without refill. The other half of the cells were filled to 45% of reservoir capacity to assess performance sensitivity near this fill value.

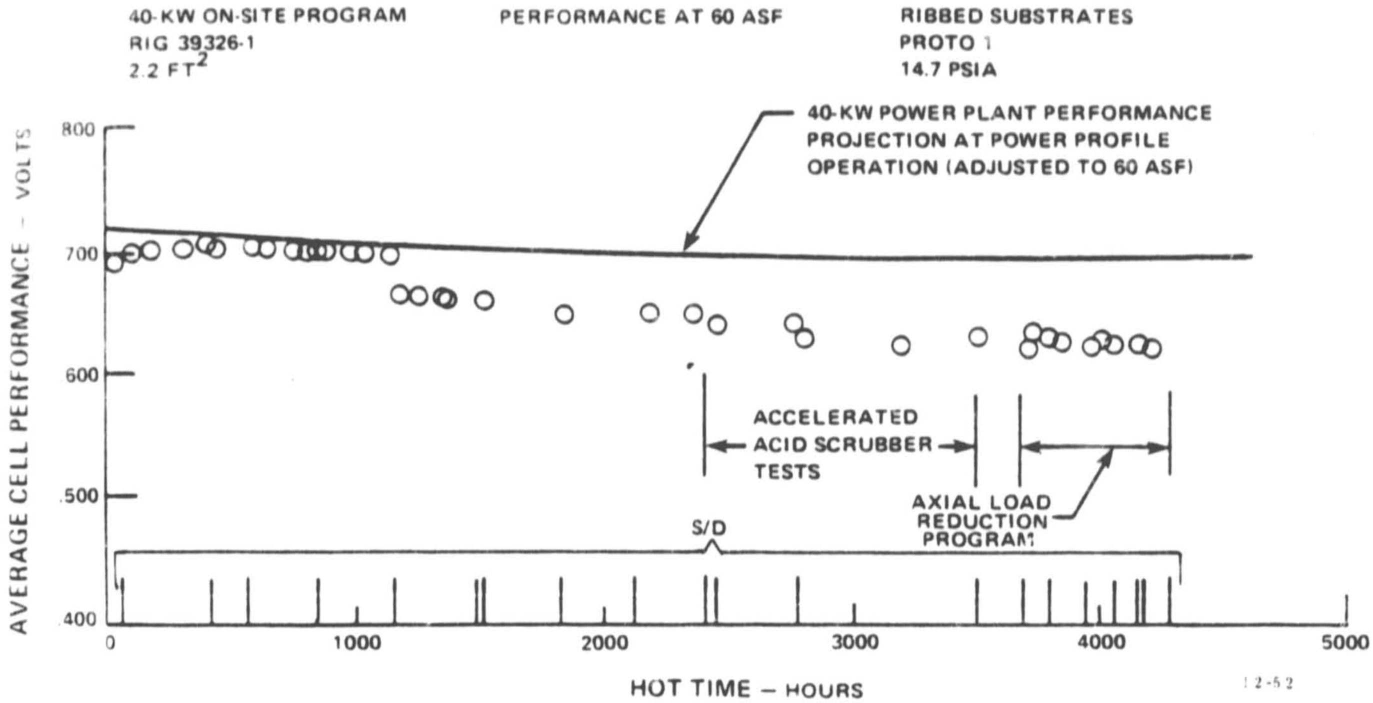

Figure 25. Proto 1 Performance and Run History

The initial performance was uniformly 20 mV below power plant goal and no difference could be discerned between the two levels of electrolyte fill for the first 1150 hours and four shutdowns. However, unlike the previous shutdowns, a severe, uniform performance penalty was incurred at the fifth shutdown. Diagnostic tests indicated the loss was due to cathode gas diffusion problem. The introduction of new test equipment into the cathode exhaust system at this juncture made contamination appear a likely cause.

A commercial pipe sealant was used in the installation of the condenser/scrubber equipment. Lab tests confirmed that the sealant will cause a performance loss by changing the wettability of the electrode structure. Testing was continued because the main test objectives of this rig were not compromised and the performance loss was concluded to be a one-time anomaly. An additional 3100 hours of testing and 16 shutdowns did not result in any further significant change in performance.

Extensive thermal probing of this cell stack was conducted in order to demonstrate that coolers at six cell intervals will maintain maximum local cell temperature below design goal of 400°F with an average cell temperature of 375°F. Figure 26, a plot of the hottest cell location in the stack, shows that satisfactory thermal control was achieved at simulated maximum design heat conditions. Although measured temperature profiles indicate some areas of the cell may be overcooled, the cell package thermal resistance is within the expected range. Cooler tube location in the cooler holder will be optimized to improve this situation.

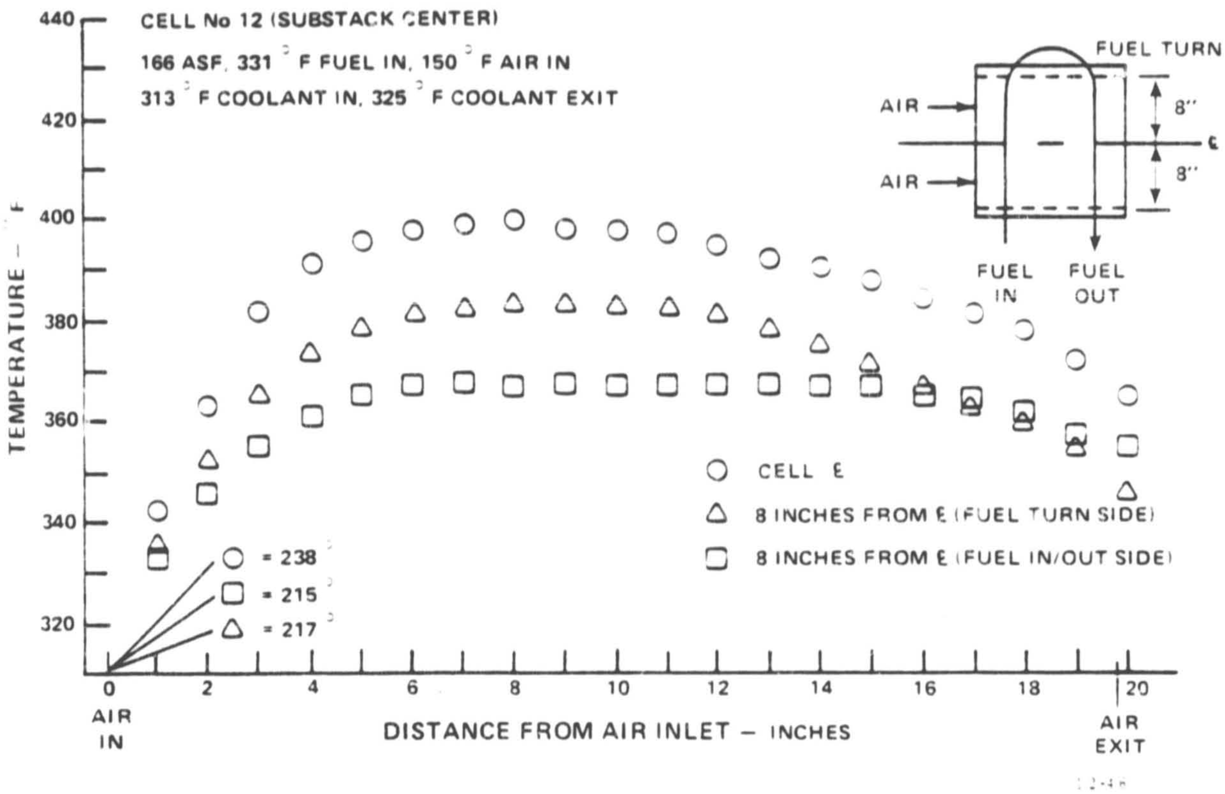

Figure 26. Rig 39326-1 Temperature Performance History

A computer program has been written to help analyze cell temperature data. The program generates a plot of isotherms from the given data, allows editing to remove or correct bad input and generates input for the cell model computer program. The contour plot, shown in Figure 27, is typical of one of six cells in a cooler group. These plots, in conjunction with local cell heat production calculated

using the cell model, are used to determine cell through-plane thermal resistance, heat transferred to the cooler tubes in the cell wet seal area and heat loss from the cell edge. This contour map, from a stack using a non-B.O.M. workhorse cooler holder, shows that the cell edges are over-cooled by a combination of process air, fuel, cooler tubes in the wet seal area and/or heat loss from the edges.

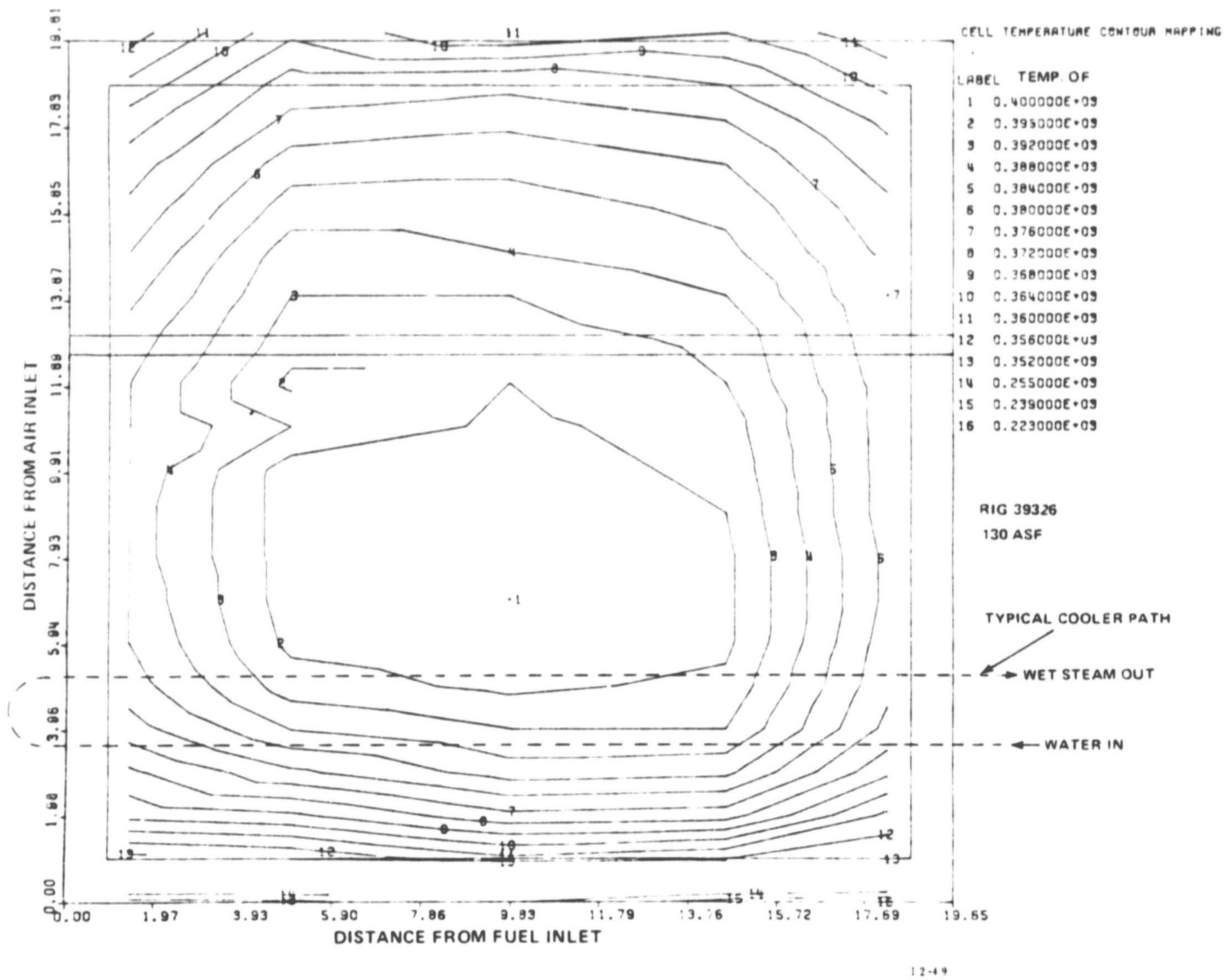

Figure 27. Contour Plot of Cell Temperature Data - Rig 39326

Analysis of thermal data from the two 24-cell stacks being run under this contract and under the DE-AC-03-76-ET11301 technology program was completed. Thermal resistance of the cooler was slightly higher than that predicted from data obtained in 4.8-MW demonstrator rigs. The through-plane thermal resistance of the 6 cell substack as determined from test data, agrees with the value used in the stack design. It was concluded that with the exception of the overcooled air inlet, the cooler design is adequate. New cooler tube spacings have been calculated to correct the cool air inlet region.

An acid condenser/scrubber system was installed in the cathode exhaust system of the Proto 1 stack at 1150 hours to generate acid scrubber design information for system studies. It completed 1250 hours of operation and was removed for analysis to support system studies. A second candidate condenser has completed an accelerated 250 hour evaluation program. The third heat exchanger configuration, a formed plate heat exchanger, was installed at the cathode exit for evaluation as a dual purpose acid condenser and process water preheater. It also completed an accelerated 250 hour evaluation program. The results of these three tests suggest that the third configuration should be incorporated into the power plant design.

The assessment of the "locked-up" axial load system after 3665 hours indicated a reduction in load to approximately 36% of the initial 19,400 lbs. However, internal cell resistance remained unchanged and reactant leakage values continued without any significant change. The last series of tests were conducted to simulate the axial loading projected for the cell stack assembly after 40,000 hours of operation. The accelerated testing was accomplished by mechanically unloading tierods in steps to simulate the normal slow load relaxation. The axial load history of this stack, the curve fit employed to extrapolate the 40,000 hour load value, and iR data obtained during the program are documented in Figure 28. Two other 24-cell stacks, Proto 2 and 3, with more up-to-date cell components continue to demonstrate similar, but improved load relaxation trends, while being tested under the supporting DOE technology program.

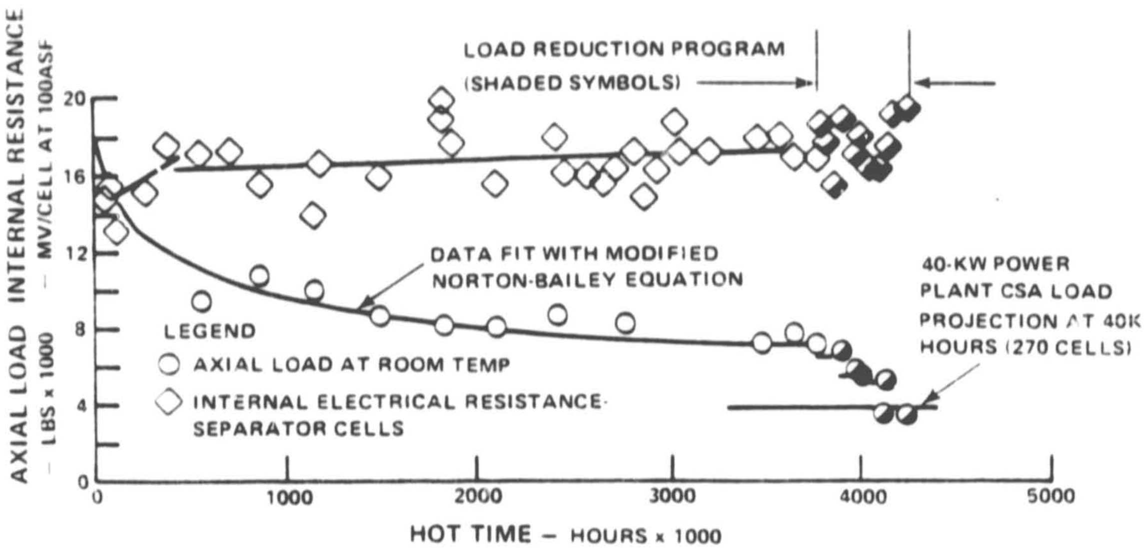

Figure 28. Axial Load and Cell Internal Electrical Resistance

The first 24-cell stack of 2.2 ft^2 ribbed substrate cells ("Proto 1") has been disassembled, and repeat parts conditioned to a known concentration to determine the acid inventory after 4250 hours of testing. The data indicates a reasonably uniform cell-to-cell electrolyte distribution with the exception of cells on either side of the cooler plates which are low in comparison with the norm. The acid loss of these cells is accounted for by electrolyte take-up of these early, solid graphite cooler holders which have been replaced by porous substrate holders that are sandwiched between the non-porous gas separate plate covers. Evaporative acid loss is consistent with design predictions. Electrode inspection revealed that all cathodes experienced some cross leakage in the substrate material in the vicinity of the edge seal. Cross leakage was not noted during inspection of a more recent 40-kW stack that was tested to 2600 hours under the supporting DOE technology contract. This stack has improved edge seals and edge joints.

The second 24-cell stack under this contract referred to as "Proto 4" was assembled and testing initiated. The major objectives of this stack are the assessment of the preliminary 40-kW power plant cell stack assembly repeat parts and the evaluation of improvements to the stack thermal control components. Repeat parts

for this cell stack were provided from the manufacturing run of parts for the 264 cell 40-kW development stack, the major features of which are:

- Improved edge seal with improved filler bands and surface preparation.
- Crimped tube cooler assemblies.
- Cooler holders with reduced bonding materials and wetproofing to reduce electrical resistance.
- Cooler tube and holder fit refined to reduce thermal resistance.
- Electrode substrate thickness reduced to improve diffusional characteristics.

This cell stack has accumulated over 1750 hours of run time and thirteen thermal cycles despite measurable stop/start losses caused by operating conditions that are somewhat more severe than anticipated for the power plant. Figure 29 shows the performance of this stack.

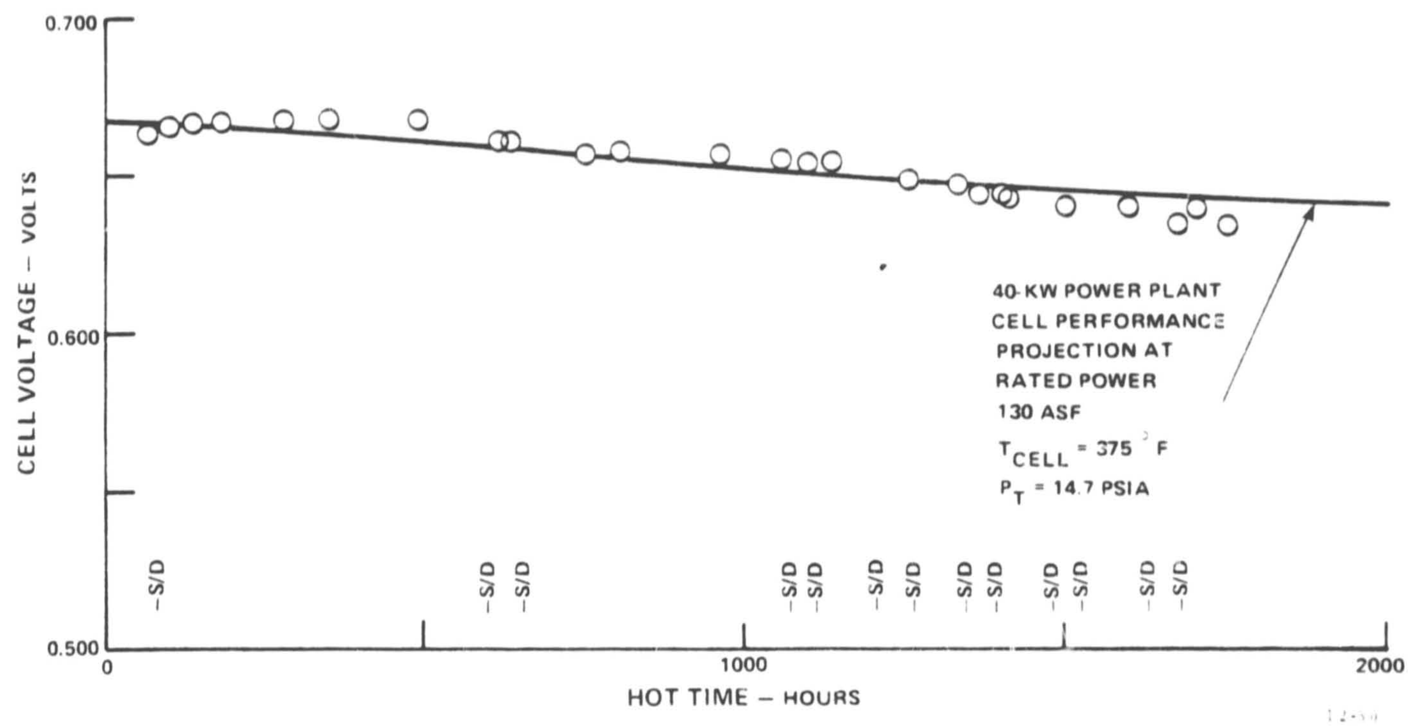

Figure 29. Proto 4 Rig 39415-1 Ribbed Substrate Performance

Based on the limited temperature data from instrumentation installed in the stack, the overall heat transfer in this stack is good. The processing variable which caused low thermal conductivity in cells and coolers of the second stack tested under the supporting DOE Contract DE-AC-03-76-ET11301 ("Proto 3") appears to be under control; thus the thermal performance of the 264 cell development stack is expected to meet the design requirements.

The other stacks of similar construction and design, Proto 2 and 3, tested under the technology contract DE-AC-03-76-ET11301, are demonstrating the desired stability of internal cell resistance and cell seal leakage. The most recent of these cell stacks, Proto 3, features the improved corrosion resistance GSA-6 cathode cells which exceeded the 500-hour design goal of .710V/cell at 24.9 kWDC by approximately 12 mV/cell. Performance of GSA-6 and GSA-7 cells at rated power (40 kWAC) conditions are shown in Figure 30. Cells (GSA-7) adjacent to and incorporating cooler electrical resistance have somewhat higher iR losses than previously experienced. This stack also features the first full-sized evaluation of the new cell edge seal and is the first 2.2 ft^2 ribbed substrate cell stack with internal fuel leakage well below the design goal. Fuel internal leakage has been determined to be less than a 0.03% power plant efficiency penalty.

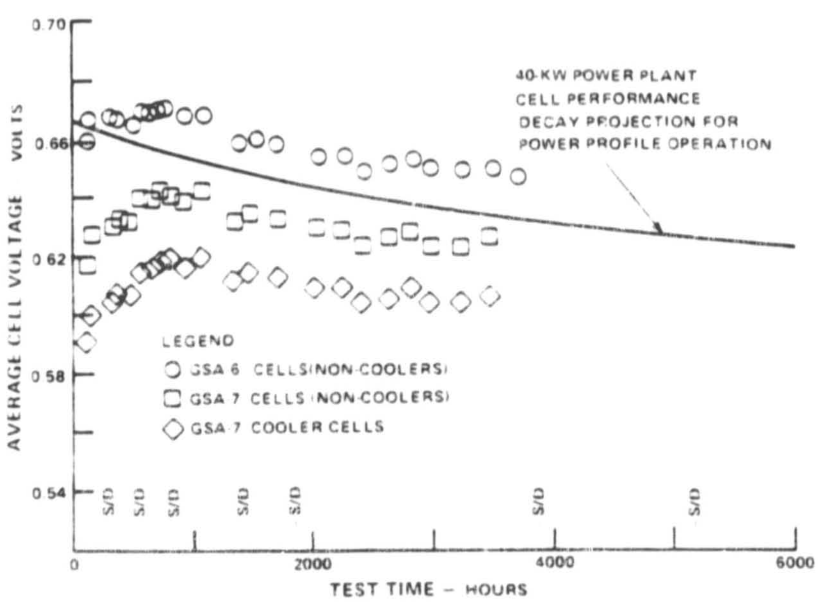

Figure 30. Proto 3 Rig 39368-1 Ribbed Substrate Performance

Power Section Assembly and Testing

Cell stacking of the first full scale power section was completed and it is shown in Figure 31. The anode and cathode substrates contain new improved edge seals while the cathodes contain the more corrosion-resistant GSA-6 catalyst. Repeat part dimensions allowed assembly of the 264 cells within the allotted stack height, thus confirming design predictions. The four tie bolts on this first full scale locked-up stack are strain gaged so that the load can be traced during heat-up and throughout the planned test program. Extensive voltage, temperature and pressure instrumentation was installed to allow analysis of the full stack performance, cooling and reactant flow distribution characteristics that can not be evaluated on short stacks.

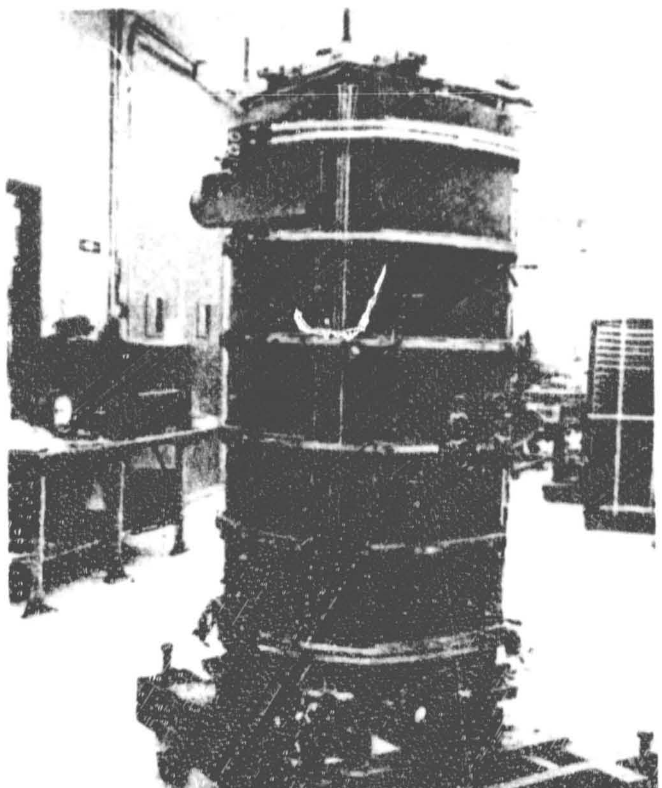

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Figure 31. 40-kW Power Section Cell Stacks

The initial test of the full-size development power section was successfully completed, and early life performance expectations were met.

Excellent fuel and air distribution was confirmed during test to utilization extremes of 90% fuel utilization and 75% air utilization at 100 ASF (80% of full power). Distribution as indicated by differential voltage plots in Figures 32 and 33 demonstrate the absence of any significant positional, reactant density, thermal, or manifold baffling effects. In addition, no significant individual cell sensitivity was noted during either of these tests designed to expose real or potential problem cells.

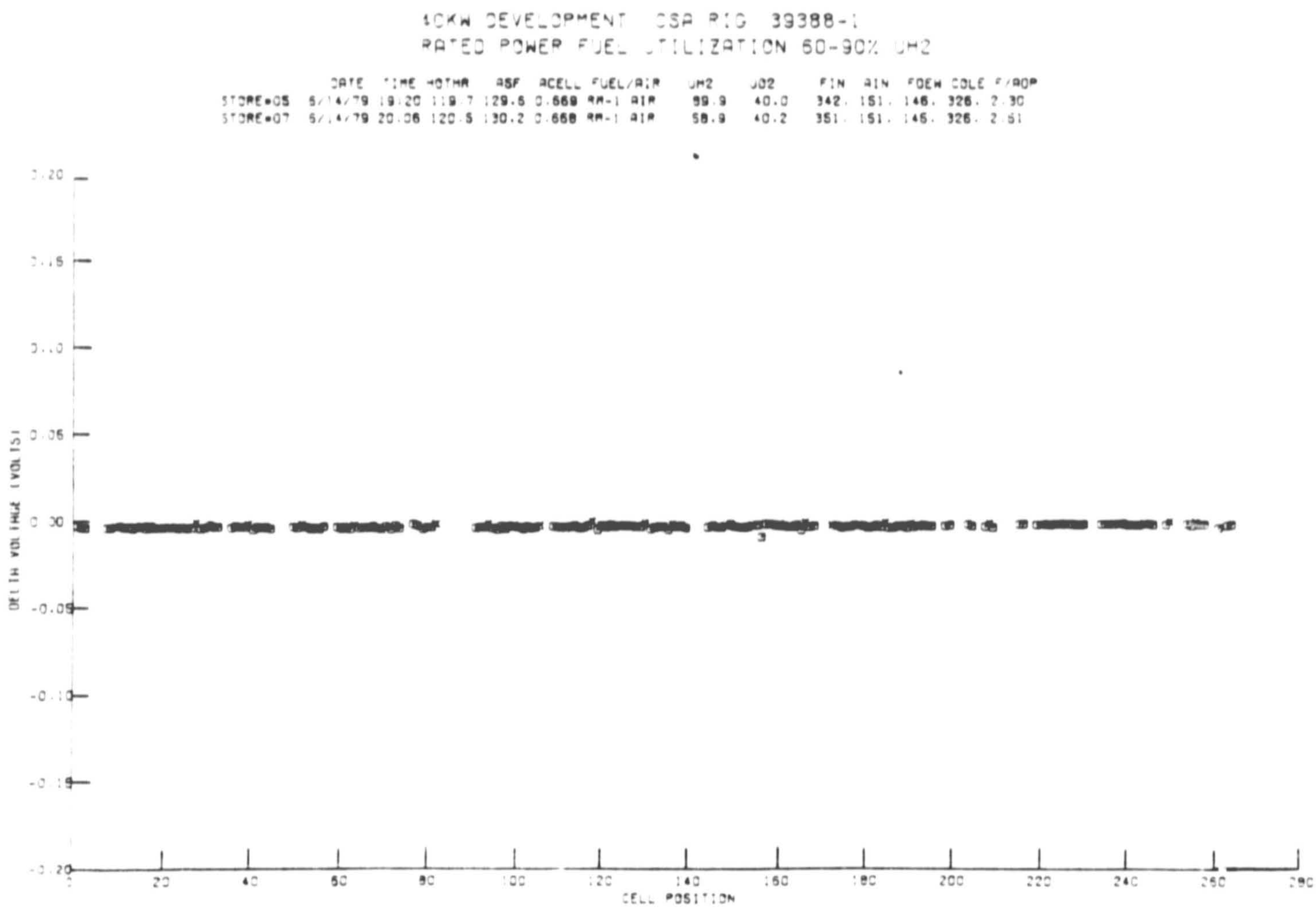

Figure 32. 40-kW Development CSA Rig 39388-1

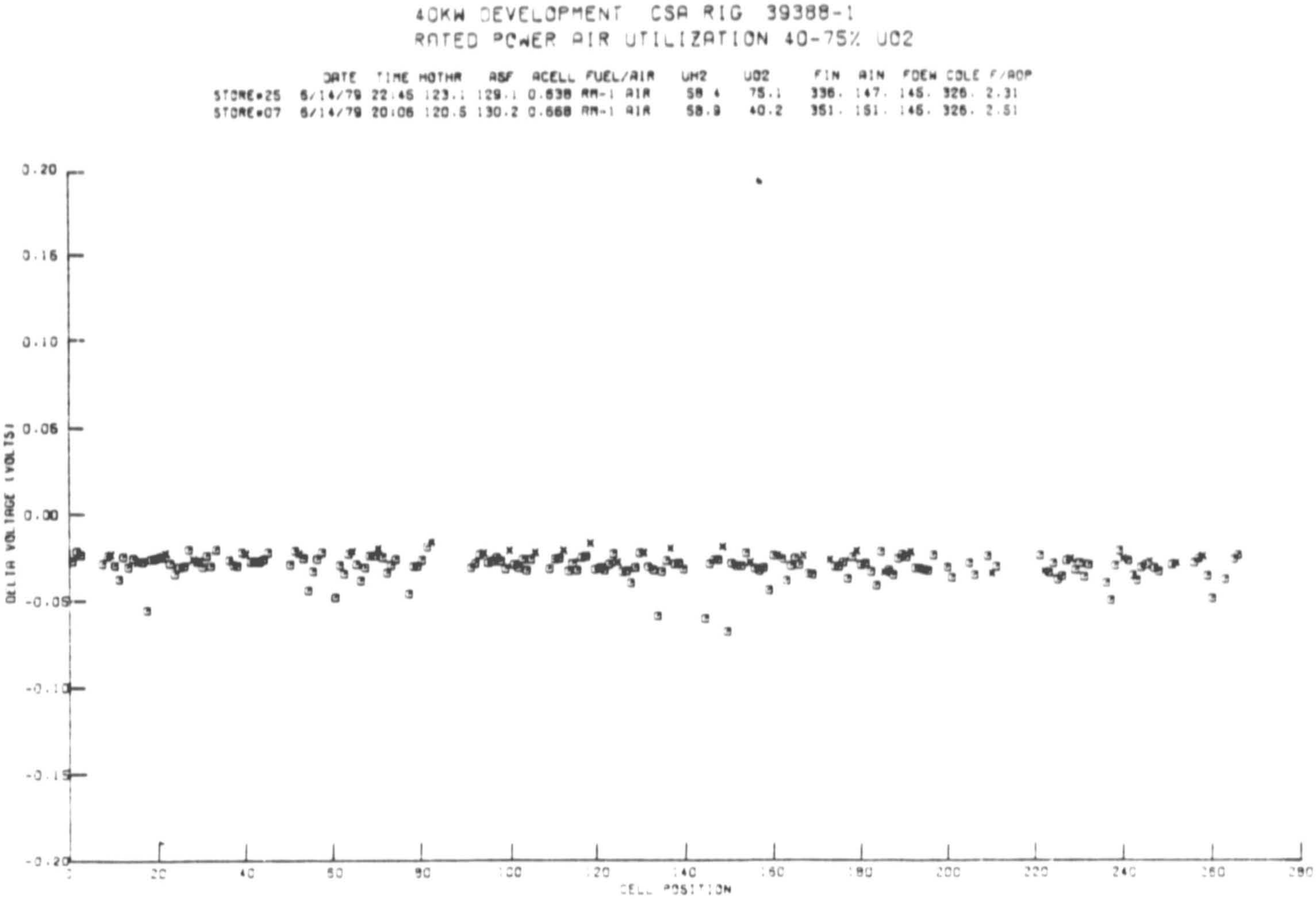

Figure 33. 40-kW Development CSA Rig 39388-1

The full scale power section has continued to meet performance objectives for over 400 hours of operation and 5 thermal cycles. Cell performance is currently averaging 5-8 mV above the 500 hour goal as shown in Figure 20. Air leakage has remained low and stable at approximately 2.0 pph as compared to the 8.0 pph allowed. Fuel leakage was approximately 0.1 pph or 1/3 of allowance. The fuel crossleakage appears to be negligible. Axial load data continues to demonstrate that the 264-cell stack is tracking the short stacks with similar repeat parts and acceptable end-of-life load projections. Analysis of thermal data from the 264-cell development power section is underway. Cell temperatures are somewhat above design values, projecting to about 405°F max cell temperature at 40 kW after 8000

hours, and 421°F at the heat rejection design point, compared to 395-400°F design max. This is not considered a serious problem in the short term since these temperatures occur only at max. power (5% of the standard load profile) and thus have relatively little impact on cell life.

The cause of the high temperature is a combination of low thermal conductivity in the cell packages (better than Proto 3, 24-cell stack, but still somewhat low) and apparently poor contact between the cooler tubes and the cooler holder. Available fixes being considered include use of a thermal caulk to improve the heat transfer in the cooler, use of an alternate electrode substrate material with higher thermal conductivity, or spacing coolers at intervals of 5 cells instead of the 6 now used.

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Design Verification of the Power Plant

Subtask 1.2.3 Inverter

> Characterization testing of the inverter breadboards from Westinghouse was completed. Both breadboards were also tested in parallel. Design and component testing of the development (brassboard) inverter and boost regulator power poles have been completed. Verification testing of the microprocessor logic system has been accomplished. The brassboard inverter assembly has been completed and testing of the unit has begun.

The objectives of the inverter effort for this reporting period were to continue the detail design effort, procure test hardware and perform component and subassembly verification tests to confirm the established design requirements. Specific goals included:

- Preparation of detailed engineering drawings and specifications for the inverter and verification of inverter performance with a design computer model.
- Completion of testing of two breadboard inverters to verify component design requirements are met.
- Completion of testing of the microprocessor logic to verify adequate control of operational functions.
- Procurement of components and assemblies for the fabrication of the brassboard inverter.
- Initiation of brassboard inverter testing.

A schematic of the power plant electrical diagram, Figure 34, shows the position of the inverter in the electrical system.

Testing of the development inverter power pole, Figure 35, has been completed and resulted in the removal of two saturable inductors from the pole design. The testing of the development boost regulator pole, Figure 36, demonstrated operation to full rated voltage and commutation of maximum load current peak.

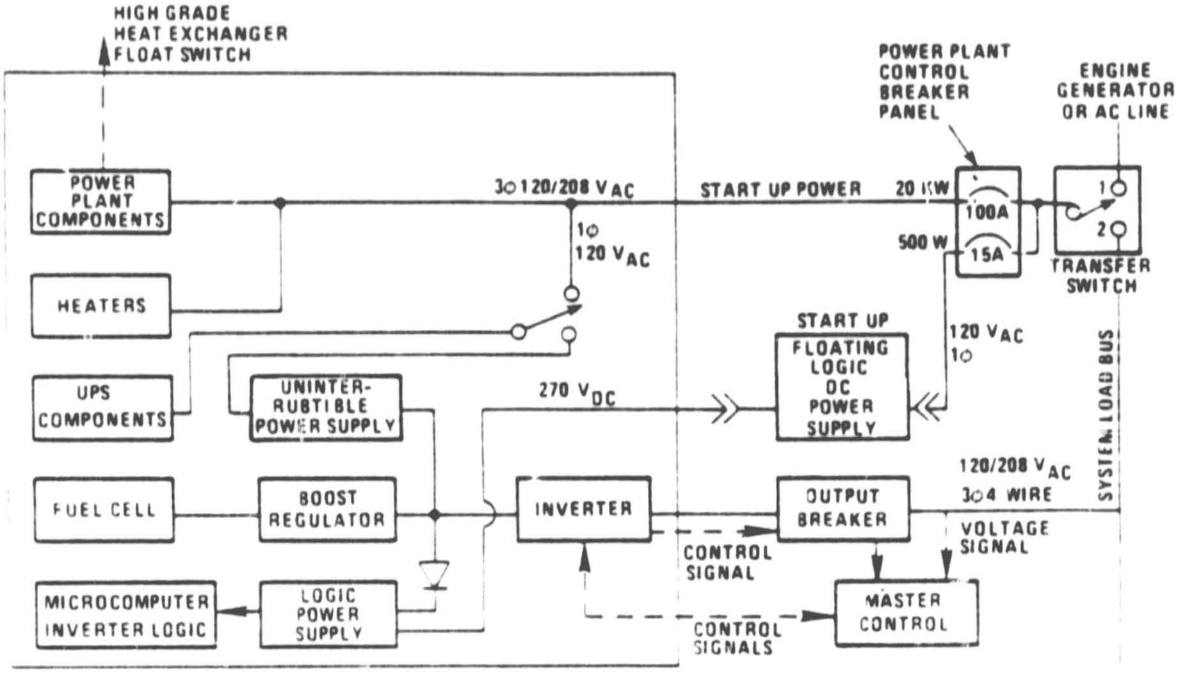

Figure 34. 40-kW Simplified Electrical Block Diagram

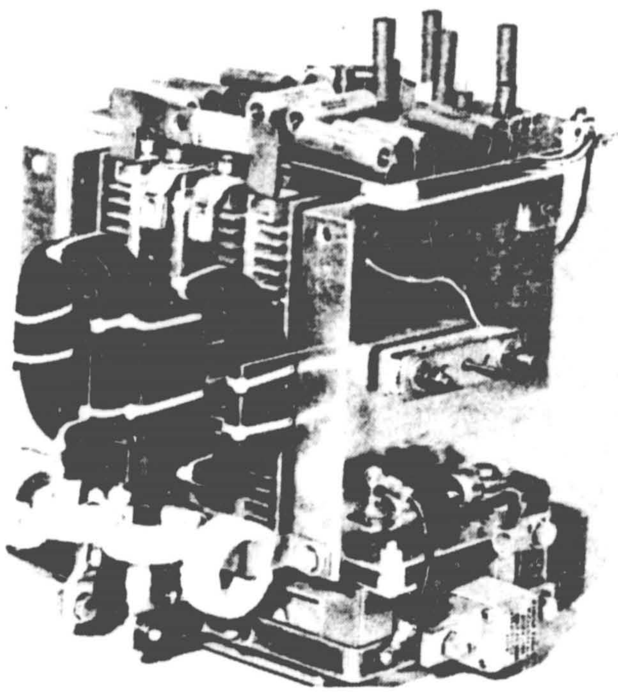

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Figure 35. Inverter Bridge Development Pole

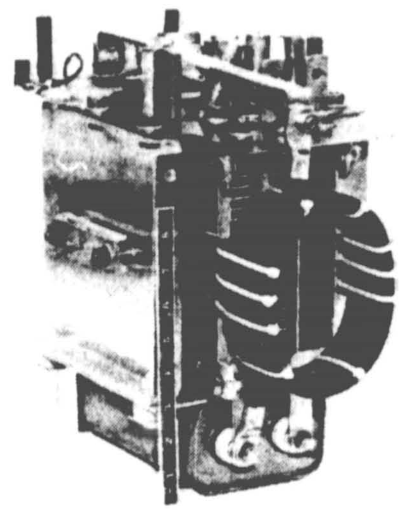

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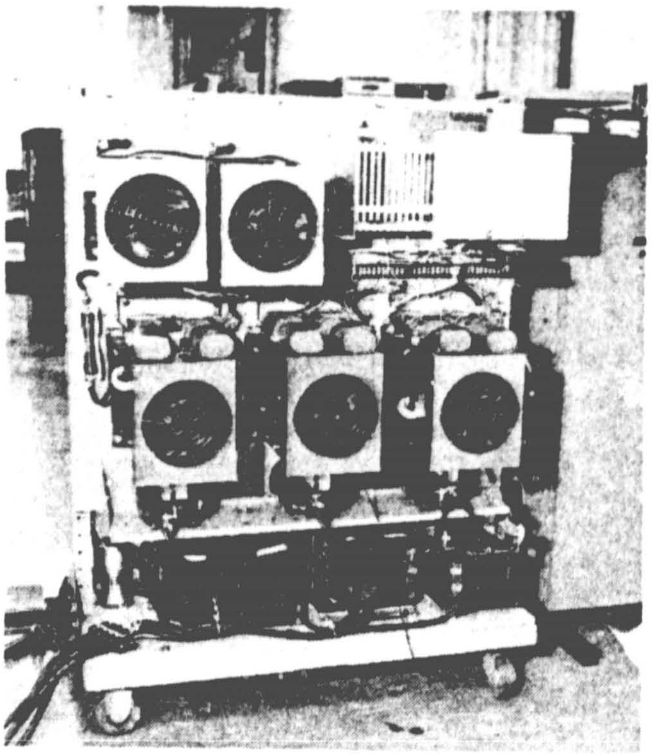
Figure 36. Inverter Development Boost Regulator Pole

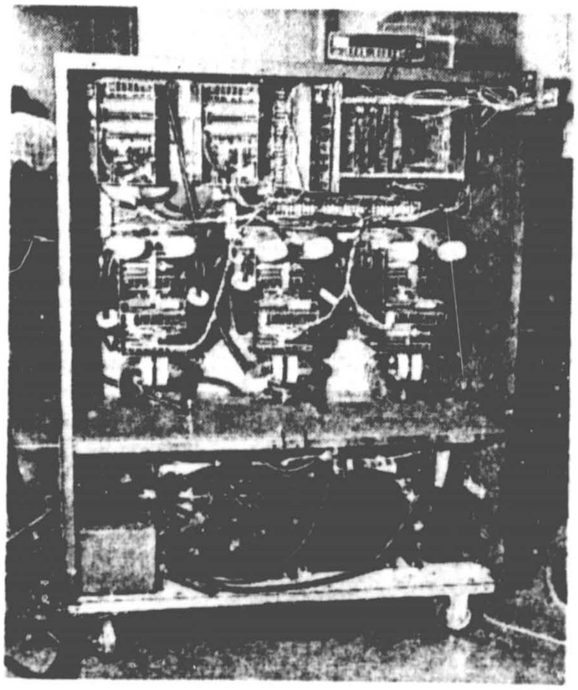
The breadboard inverters, Figures 37 and 38, were received from Westinghouse and operated at rated power, meeting both booster and inverter efficiency specification goals. Breadboard inverter efficiency levels of 86.2% at 30 kW and 89.5% at 40 kW were measured. Operation and performance deficiencies in the breadboard inverters were corrected. These modifications included:

- o A logic programming change to speed-up the ac output voltage regulator response time to step load changes from seconds to milliseconds.
- o Logic reprogramming that properly activated parallel load sharing control of each inverter from an error signal derived in the master control unit (MCU).
- o Logic reprogramming that allowed activation of ac undervoltage/overvoltage protection for both single unit and parallel selective trip.
- o Addition of a main feed contactor control relay/logic interface circuit for paralleling of units and selective trip of paralleled units.
- o Logic reprogramming to correct an ac output voltage control stability problem for load up and down transients in the range from 10 to 3 kilowatts.



(WCN-6084)

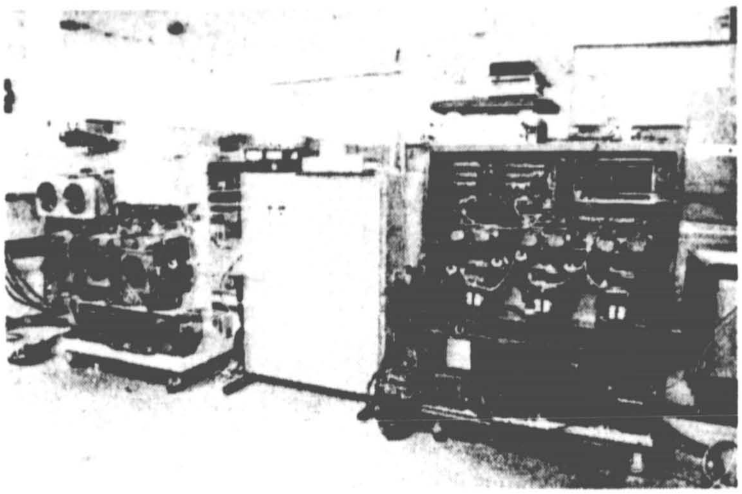
Figure 37. Breadboard Inverter No. 1



(WCN-6062)

Figure 38. Breadboard Inverter No. 2

Both inverters were characterized for proper operation under steady state and transients to rated load conditions. The units had comparable ac output voltage characteristics. Protective functions for ac over/under dc link over/under voltage, abnormal frequency and blown fuse shut-down operated properly. The test facility for parallel operation, Figure 39, was finalized and instrumented.



(WCN-6390)

Figure 39. 40-kW Inverter Parallel Test Facility

Breadboard inverters were operated in parallel over the load range from 9 kW to rated load. The sharing between the two units was acceptable (within 5%) and demonstrated that the control philosophy was sound. The units were also loaded beyond peak power up to the present capacity of the load system and exhibited stable sharing in current limit up to a reduced AC output voltage of 65 VAC.

Bolted fault short circuit testing of breadboard inverter number two was conducted for both line-to-line and line-to-neutral faults. Proper logic operation and control were demonstrated while maintaining pole currents within the 400 ampere upper limit. Successful operation up to the design level of 5 seconds under balanced three phase bolted faults was demonstrated. Some unanticipated fuse clearing was encountered under unbalanced line-to-neutral and line-to-line bolted fault conditions. This was corrected by changing the location of pole output current sensing shunts, by careful re-dress and routing of sense and gate drive cables, and by shortening the connection between the power poles and the interstage capacitor bank.

Breadboard unit number one was modified to incorporate all the hardware and software changes identified during current limit testing of breadboard unit number two. Short circuit tests of breadboard unit number one confirmed that it performs as well as unit number two. Both units continued to have a small number of random fuse clearing difficulties under certain line to neutral faults which should not have a significant effect on parallel fault testing. The brassboard unit has been designed to eliminate these problems. Testing of the two units in parallel has shown no system instability, and they share currents delivered to fault remarkably well, Figure 40. All types of line and phase fault configurations were run for the full five seconds. Nuisance output breaker trip signals and DC unbalance protective shutdowns were eliminated by minor microprocessor reprogramming.

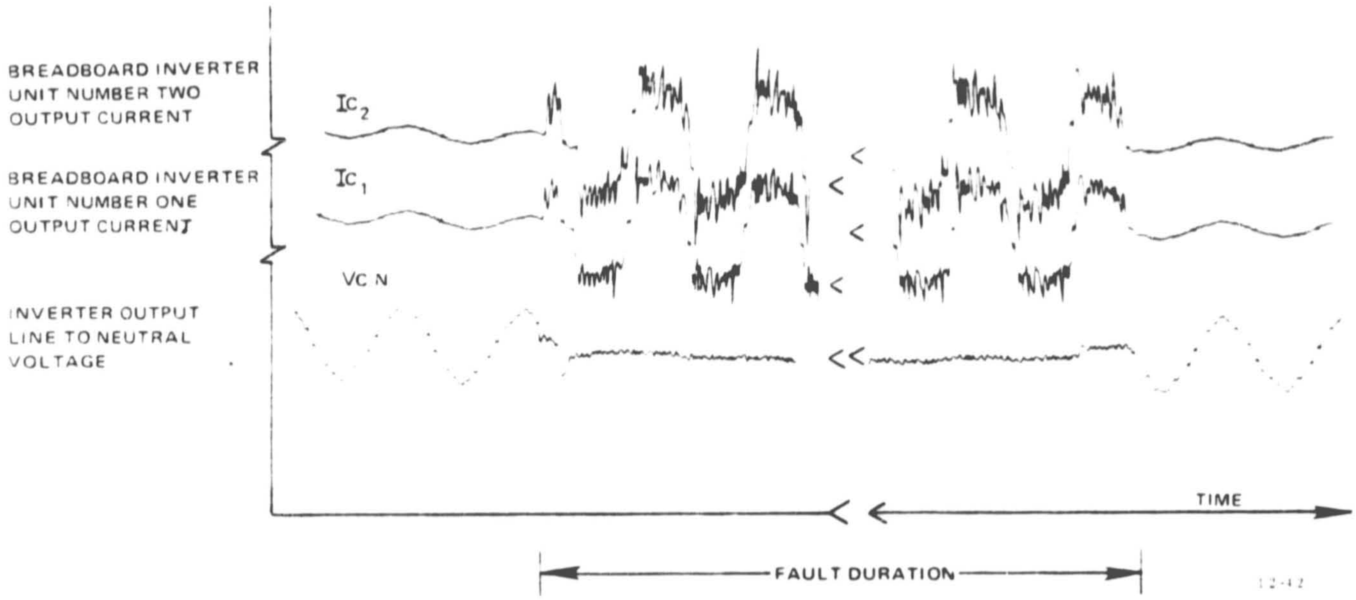


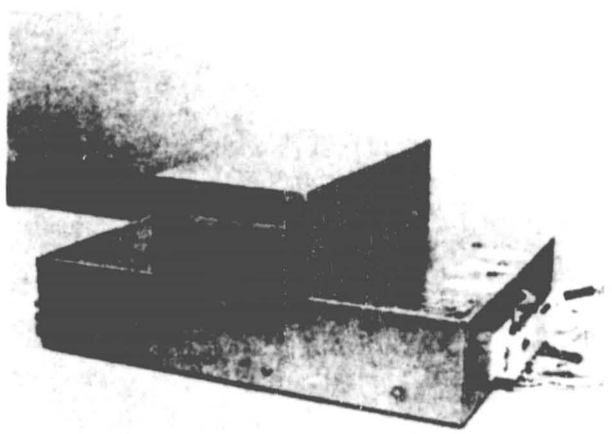
Figure 40. Parallel Operation of Breadboard Inverters

The testing of the breadboard inverters was completed with the successful demonstration of selective power plant shutdowns. Various abnormal operating conditions and simulated system failures were tested, and in each case the proper inverter was safely isolated from the system load bus.

A master control unit (MCU) Component Design Requirements (CDR) was written and reviewed. The MCU is used to parallel multiple 40-kW inverters to a common load bus. The basic sharing control philosophy was demonstrated with the breadboard hardware. This testing formed the basis of the brassboard MCU design

The breadboard Master Control Unit (MCU), Figure 41, was assembled and bench check-out was completed. This unit provides the synchronization signal for both inverters and appropriate load sharing error signals for each inverter. Integration of the MCU with the two breadboard inverters was accomplished. Both inverters were successfully operated individually and simultaneously (non-parallel) with no observable phase shift in output voltages over a load range from no load to full load and for unbalanced phase loading to 30%. Open loop testing also verified that MCU load sharing error signals were correct and directly proportional to the sensed deviation from the average total load current as shown in Figure 42.

As a result of a preliminary design review of the verification master control unit (MCU) it will be capable of operating up to three power plants, and another slave MCU will operate additional power plants. The brassboard MCU, except for the load shedding circuitry, is ready to be tested with the breadboard inverters.



(WCN-6391)

Figure 41. 40-kW Breadboard Master Control Unit

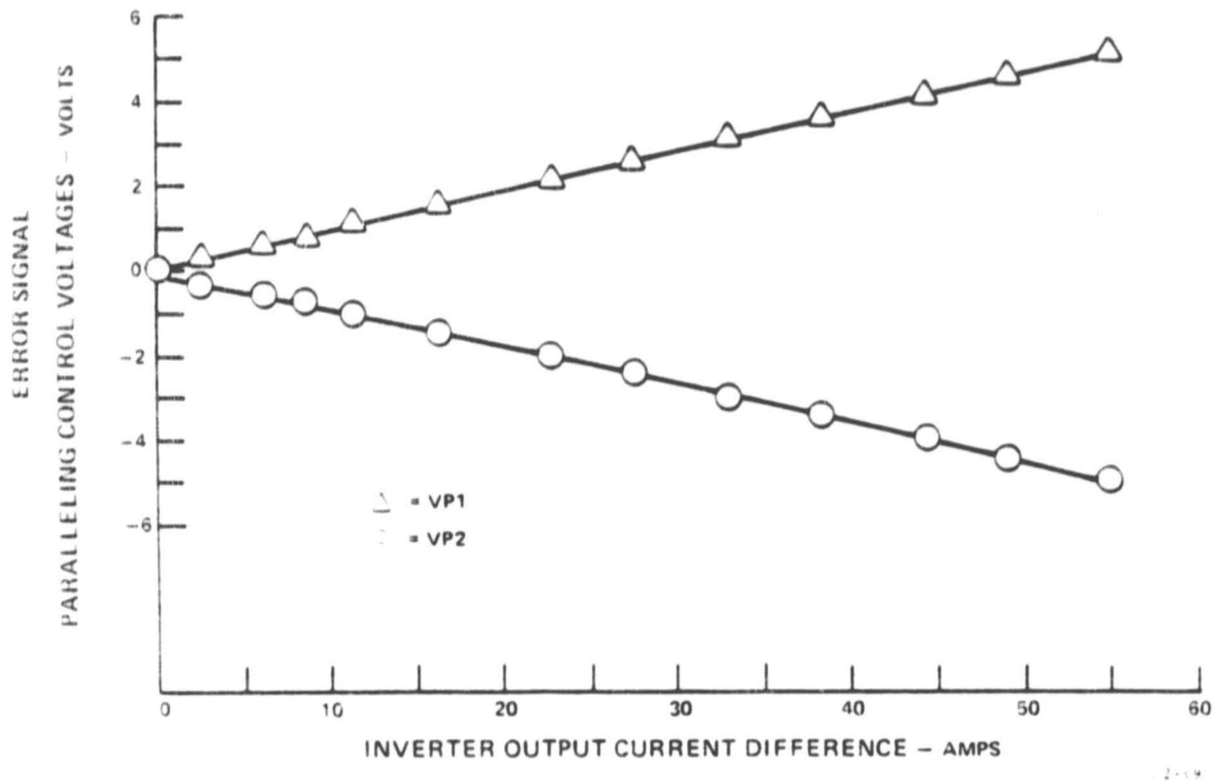


Figure 42. MCU Paralleling Control Error Signals are Linear and Proportional to Sensed Current Difference

The F-8 microprocessor development system was used to update all microprocessor logic programs. Brassboard logic design is underway, with present emphasis on optimizing pulse width modulated (PWM) wave form program and current limit control.

The conceptual design of the brassboard inverter was completed using component sizing information from the development pole layouts and the breadboard inverters.

The brassboard inverter assembly was completd, Figure 43, and electrical testing was completed using logic from breadboard inverter unit number one. Testing included checkout of the dc link/capacitor assembly to maximum system voltage and operation of the inverter into the output filter section to 18 kW at 0.85 pf. The output section exhibited a total harmonic distortion (THD) at 18 kW of 11% which is better than specification limit of 15%. As a result of brassboard RCT power pole

checkout, it was discovered that the gate drive in the breadboard logic was insufficient to turn on the one inch RCT's correctly. The drive was modified to correct this, and static full voltage and low voltage dynamic testing was successfully completed.

(WCN-7194)

Figure 43. Brassboard Inverter Assembly

The three power poles were operated dynamically to 275 VDC without, and then with, the output magnetics connected. The boost regulator was then tested independently of the inverter power poles. During testing of the boost regulator operating with the power poles, an RCT failure occurred. The cause of the failure was a logic problem producing variation in the pulse width of the first gate drive signal during start-up thus causing improper turn-on of the RCT, resulting in pole fuse clearing. Corrective action was taken to modify the breadboard logic used in the brassboard testing and to insure that the brassboard and verification inverter logics do not have similar problems.

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Design Verification of the Power Plant

Subtask 1.2.4 Controls

> Specifications were completed for all control components, including the microprocessor. Specifications were used to solicit candidate control components from vendors. Bench testing of these candidates resulted in the selection of components for the verification power plant. The software for the microcomputer system was written, edited, debugged and run during the testing of the microcomputer.

Objectives for the control activities during this period were to continue the design of power plant controls and to conduct bench tests and verification tests of components and subsystems to ensure consistency with design requirements. Specific goals include:

- Prepare engineering drawings and specifications for control components prior to purchasing or fabricating activities.

- Design, construct, and evaluate the electronic supervisory system using microprocessor based logic.

- Procure control elements for testing.

- Conduct verification and acceptance tests of mechanical, electrical, and supervisory controls to demonstrate adequate control of the subsystem functions required by the component design requirements.

Design Activities

Design approaches for both the fuel control and air control were selected and preliminary engineering drawings prepared. The fuel control design chosen integrates the steam ejector, fuel feed and H_2 recycle functions and uses a common actuator and feedback device. The air control design provides for independent control of the reformer burner and power section air flows by using separate

sliding gate valves. Each gate valve requires an actuator and feedback device for control operation. The preliminary and final design reviews for the fuel and air controls were held, and the final design layout of the air control valve was released for fabrication. One cathode air valve and two burner air valves were fabricated for development testing.

A preliminary three-line wiring diagram identifying all the power plant control signals and components and describing the wiring requirements of each was prepared. This diagram specifies the connector designations used to interface each signal and component with the microcomputer or power distribution center and microcomputer instrumentation and diagnostic signals. The prototype power plant wiring harness was fabricated following construction of a model wiring harness using the power plant as a hard mock-up.

The electrical design schematics for the microprocessor logic, signal conditioning and low power drivers were completed and design reviews were held.

A microprocessor logic design for the 40-kW microcomputer was completed. This microprocessor logic card design centers around the Motorola MC6802 microprocessor and is diagrammatically shown in Figure 44. The significance of this design approach is the reduced number of logic components and Erasible Programmable Read Only Memory (EPROM). The MC6802 microprocessor features consisting of resident Random Access Memory (RAM) two-phase clock oscillator, and an INT-2716 memory device, allowed elimination of discrete components for these functions. This new memory device also provides twice the storage capacity of the device being used, providing future design flexibility. The circuitry used to evaluate this design is shown in Figure 45.

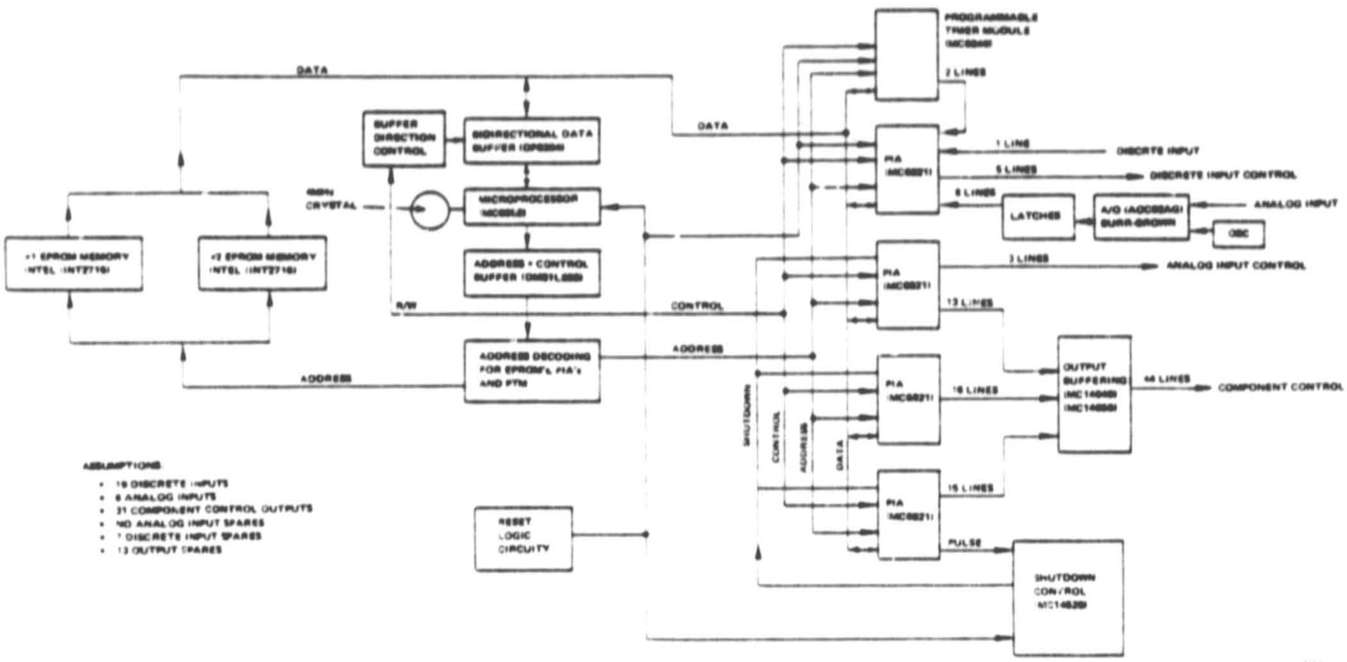


Figure 44. Microprocessor Logic Card

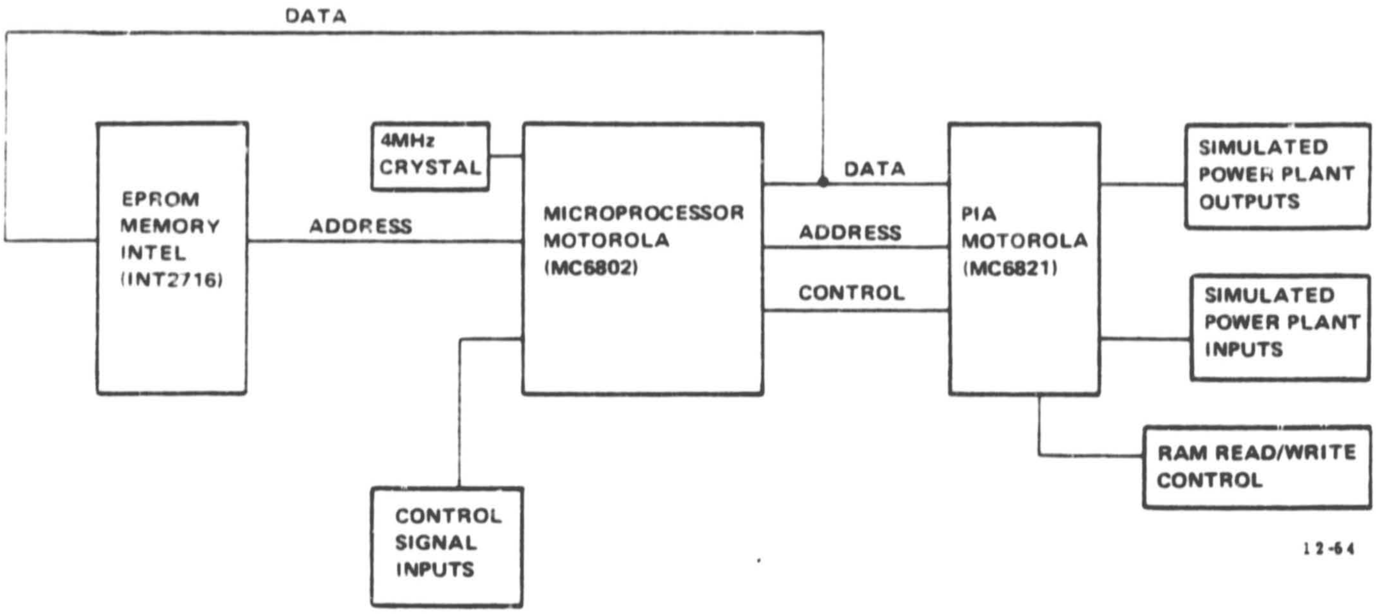


Figure 45. Microprocessor Evaluation Test Circuit

A preliminary design of the microprocessor logic circuitry with back-up shutdown capability for the prototype 40-kW power plant was begun. This design approach is similar to the pilot 40-kW power plant design, except for the additional microprocessor and peripheral components necessary to provide the backup shutdown. Because additional and more complex logic circuitry would be needed to select the primary or back-up controlling microprocessor, an alternative analog method to providing this capability was investigated. One approach was to use the internal logic circuitry of the PIA (Peripheral Interface Adapter) to gate all AC driver outputs to the off state if the microprocessor fails. This results in the de-energization of all power plant control components. The analog circuitry design was breadboarded and successfully tested with the MC6802 microprocessor.

Multiplexing techniques for analog and discrete input signals to the 40-kW microcomputer were investigated as a means of reducing the number of card-to-card signals. The multiplexing is accomplished through hardware switching devices controlled by software programming. The discrete signals are multiplexed by one of three "8 channel data selectors" as shown in Figure 46. This reduced from 24 to 6 the number of signals transferring from card-to-card. The analog signals are multiplexed by an "8 channel single-ended analog multiplexer" to an analog-to-digital (A/D) converter, Figure 47, thus reducing the number of control signals from 8 to 3. Analog-to-digital control through software programming was also investigated. This control approach eliminated the need for data latches and control logic presently required for A/D operation.

A design of the signal conditioning circuitry was completed. This circuitry interfaces power plant control sensors with the microprocessor logic. Its functional block diagram is shown in Figure 48.

Final specifications for the various control components were completed. These components were bench tested to evaluate performance using test rigs that closely simulate power plant conditions. Outlined below are the components evaluated in this manner.

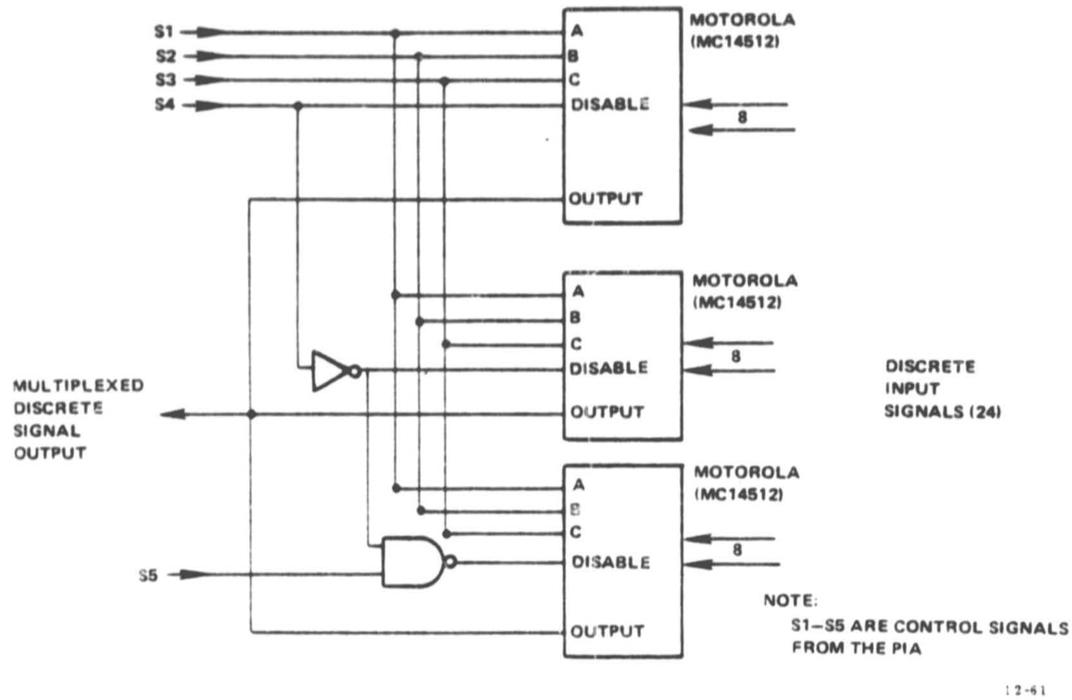


Figure 46. Discrete Input Multiplexers

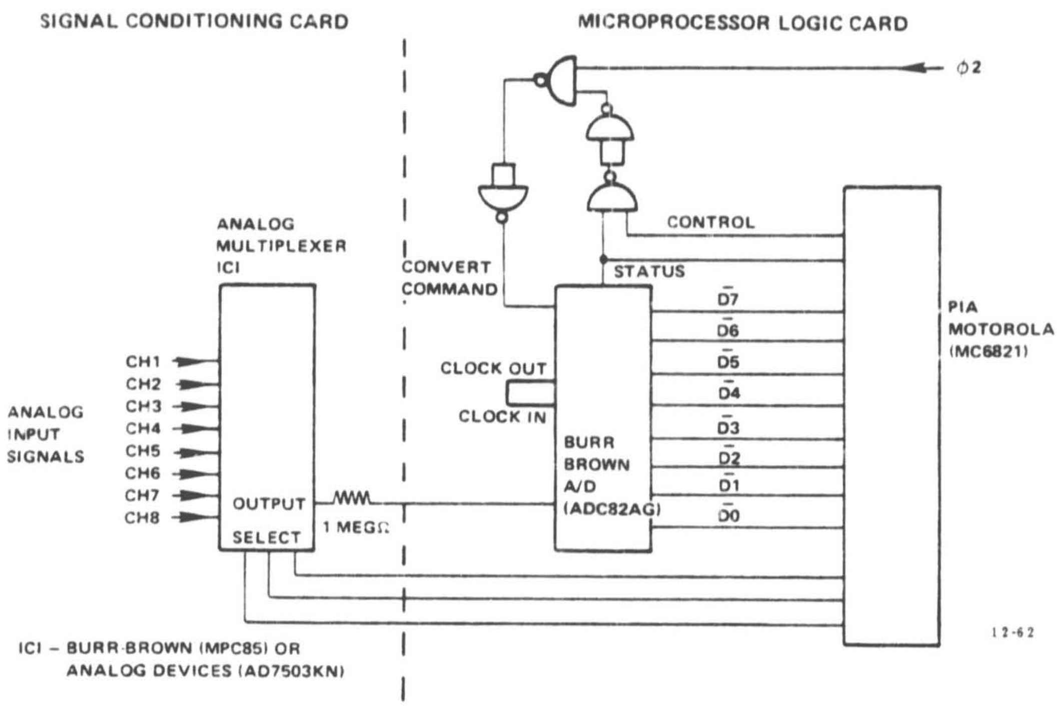


Figure 47. Analog Input Multiplexing Scheme

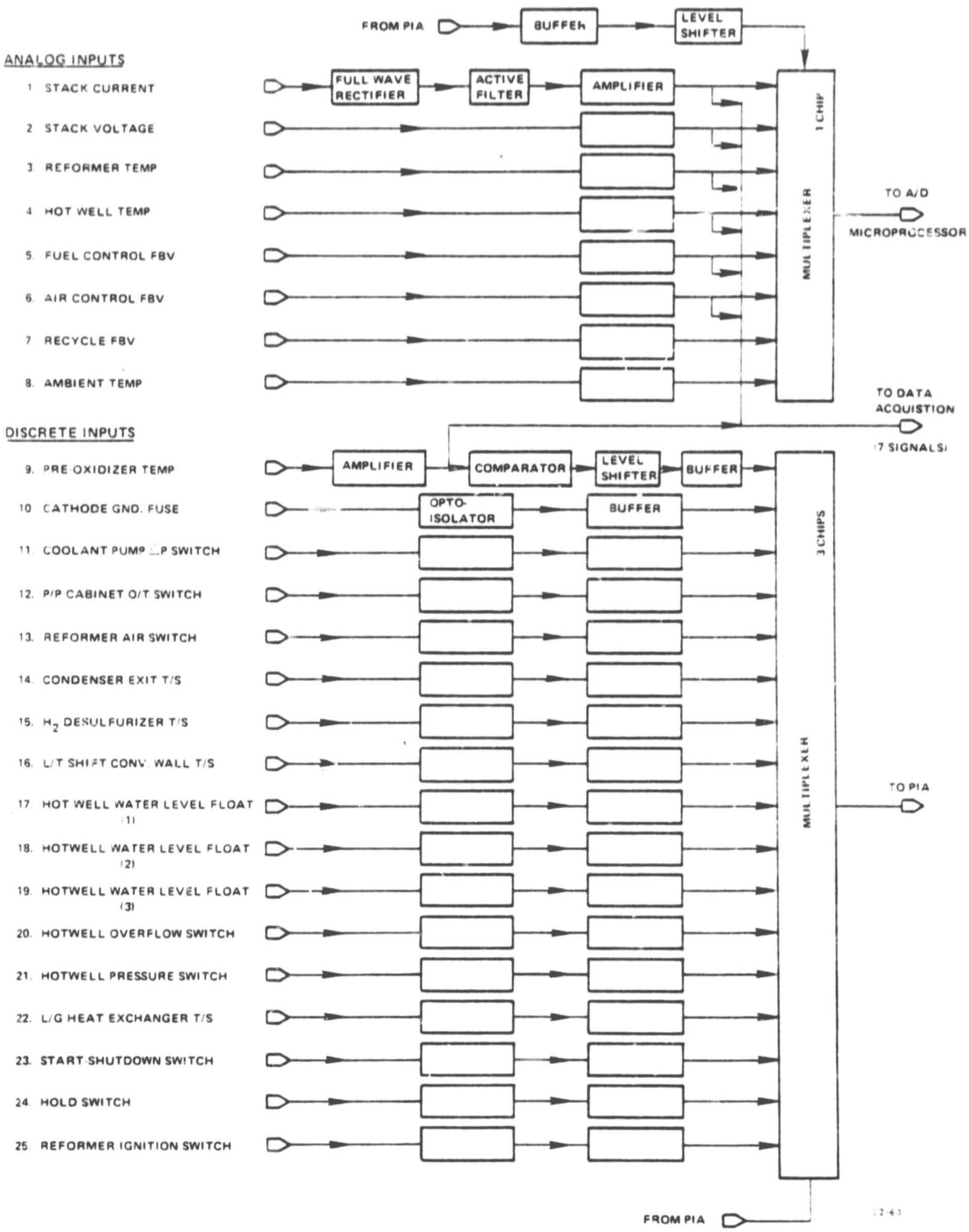


Figure 48. 40-kW Signal Conditioning Board

TMS Microcomputer

The TMS test rig microcomputer was restarted and controlled in operation satisfactorily. During a controlled rig shutdown the microcomputer system was damaged due to an electrical short within the steam ejector/motor assembly. Several failed components on the microprocessor logic card and the driver circuit cards were discovered and replaced or repaired, bringing the unit to an operable status. Due to existing similarities in the designs of the TMS and 40-kW microcomputers, design criteria to preclude this failure from recurring in the 40-kW power plant was established.

Microprocessor

Bench test evaluations of the MC6802 microprocessor, analog and discrete multiplexers, A/D converters and analog back-up shutdown circuitry were completed. The performance of two candidate analog multiplexers with the A/D converter was evaluated. These components were assembled as a breadboard, Figure 49, for testing in close proximity with the breadboard inverter to evaluate the effect of operating the microprocessor logic in an electro-magnetic interference (EMI) environment. The results demonstrated that the logic was not susceptible to EMI, thereby eliminating any shielding requirements. This EMI test will also be performed on both the microprocessor logic and signal condition breadboards.

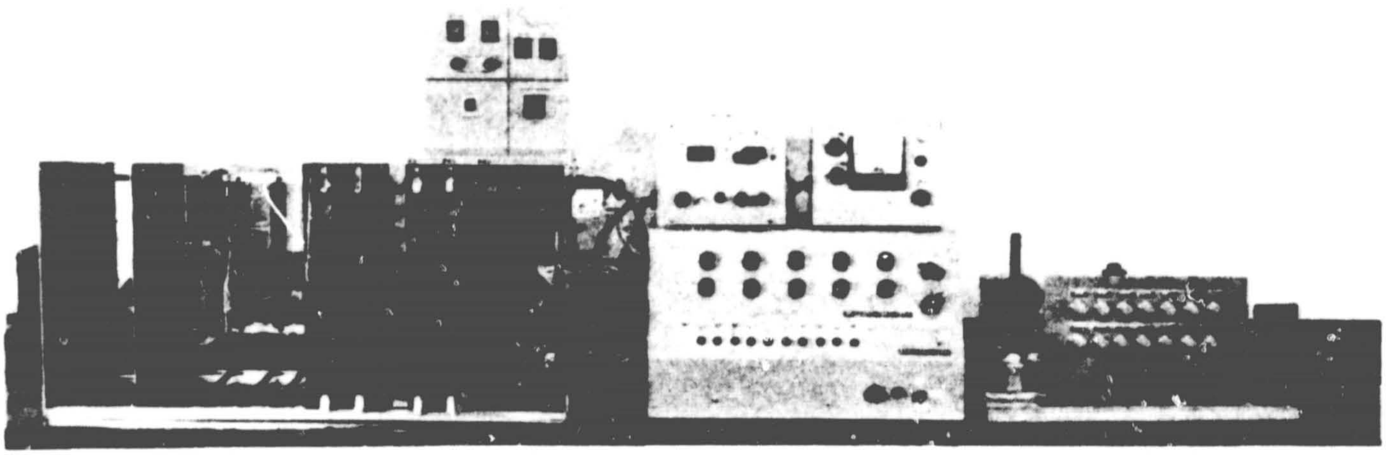
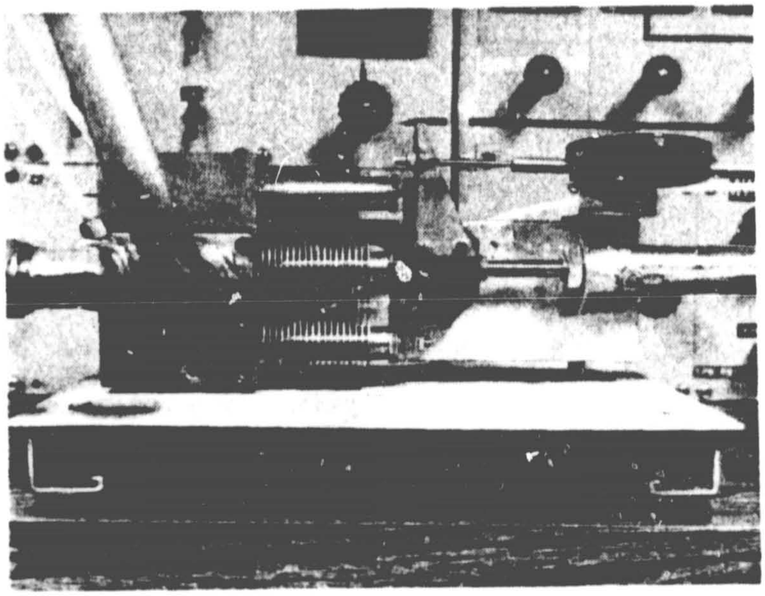


Figure 49. Bench Testing of the Prototype Microcomputer (W-4609)

Integrated Fuel Control

The fabrication of the detail parts for two integrated fuel control assemblies was completed. The first unit was installed into the test stand, see Figure 50, and testing was started. Some modifications were necessary to improve the ejector position versus flow characteristics. Pintle and seat modifications were made to improve valve characteristics. Both the ejector and recycle valve are providing acceptable performance as the testing continues.



(W-4574)

Figure 50. Integrated Fuel Control

Air Blower and Air Control Valves

A test rig was fabricated to evaluate the performance of the process air blower and air control valves. This rig closely simulates the cathode and reformer burner air loops and allows for the monitoring air flow and pressure differences. Continuity of process air during power interruptions was considered highly desirable. Testing of a flywheel with the process air blower configuration showed only a 12 percent reduction in air flow during the five second power interruption, Figure 51. This approach satisfies the CDR requirements and reduces considerably the uninterruptable power supply (UPS) requirements. Performance testing of the

development reformer burner air valves has indicated that slight redesign to valve areas was necessary; this was done. Figure 52 shows the air control valve. The performance of both valves is acceptable, and leakage is less than 1/2 percent of maximum air flow. Continued durability testing is planned. Testing of the air control valves using a microprocessor control system to evaluate closed-loop operation is also planned. One of the development air valves placed on cyclic endurance to evaluate the durability of the slide materials has accumulated 720 hours (205,000 cycles) without any signs of wear as of 15 May 1979.

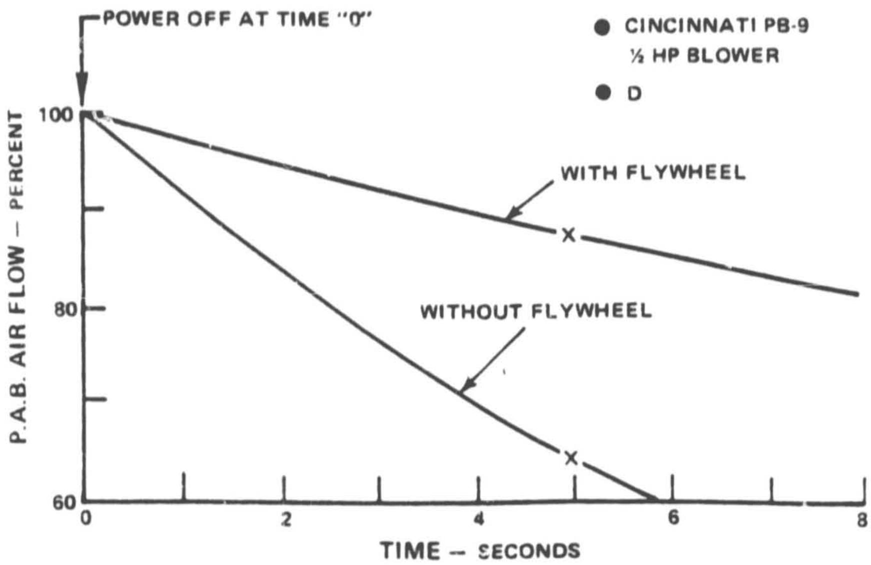
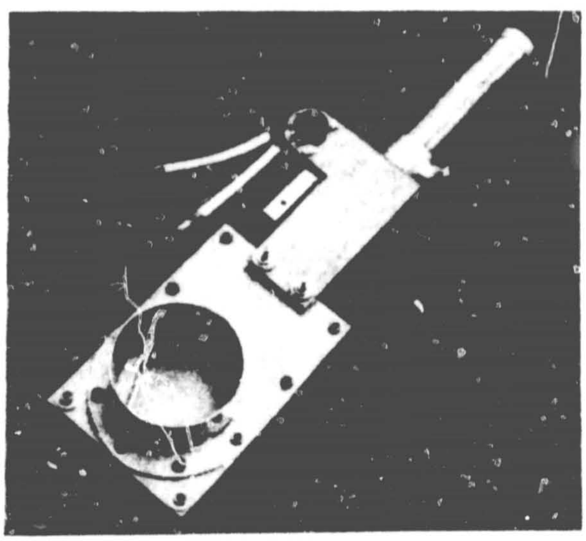


Figure 51. 40-kW Process Air Blower Flow vs. Time



(W-4560)

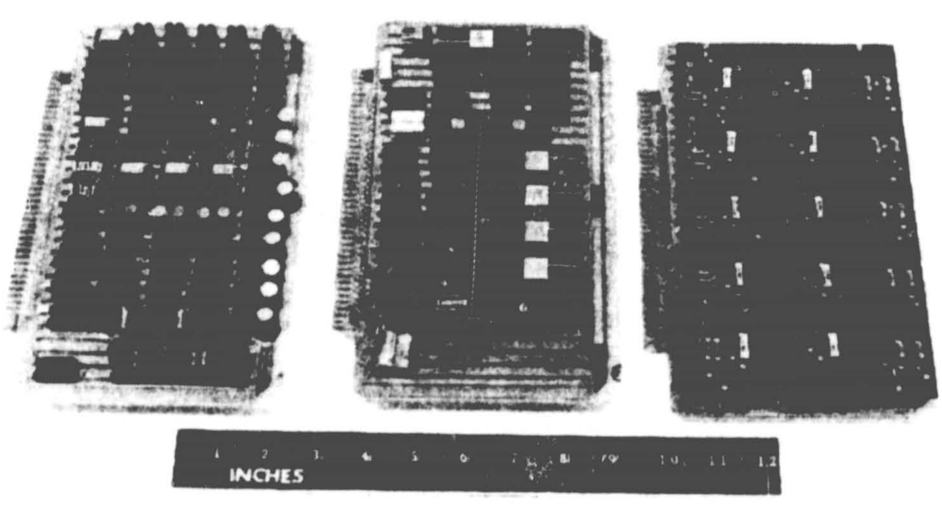
Figure 52. Prototype Air Control Valve

Heat Exchanger Bypass Valve

A three-way diverter valve and single actuator design approach was selected. Performance and high-temperature operation were evaluated during bench testing. Two types of rotary solenoid actuators and a water pressure actuator, similar to the type used for the air control valves, were evaluated. Performance of the rotary solenoids was determined to be unacceptable for power plant use. The water pressure actuator was coupled to the bypass valve for further evaluation.

Breadboard Microcomputer Supervisory System

The fabrication of a breadboard microcomputer supervisory system was completed. The system consists of the microprocessor logic board, the signal conditioning board, the low power driver board, and the microcomputer chassis as shown in Figures 53 and 54. To aid in the bench testing of the breadboard microcomputer, a power plant electronic simulator was constructed. This simulator provides the necessary analog and discrete input signals to the microcomputer simulating power plant operation, Figure 55.



(W-4483)

Figure 53. 40-kW Microcomputer Breadboard Cards

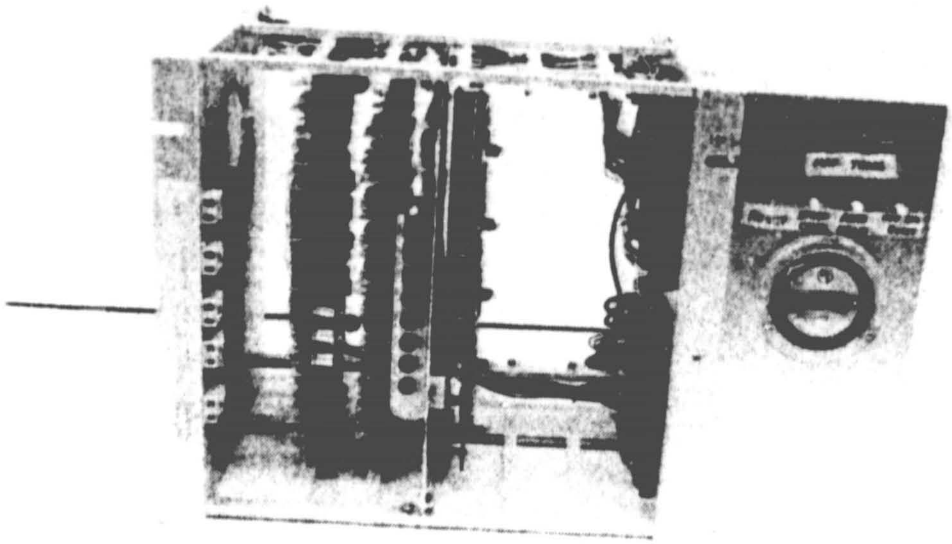


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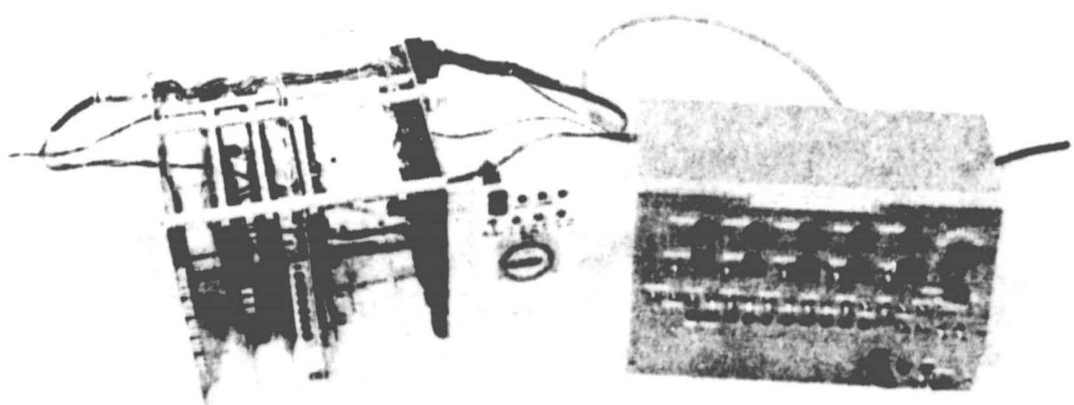
Figure 54. 40-kW Microcomputer Breadboard Rack



(W-4484)

Figure 55. 40-kW Microcomputer Breadboard Rack and Power Plant Simulator

The breadboard microcomputer was bench tested using the electronic power plant simulator and diagnostic software. The software was developed to verify all of the microprocessor controlled input and output signal functions. A power plant component load simulator was also fabricated to verify the microcomputer low-power

output drivers using A.C. loads. The microcomputer has been successfully operated at an elevated temperature environment (80°F to 130°F) to evaluate system performance and stability. The microcomputer software package, consisting of 30 linked routines from start-up through transition, has been successfully verified using this breadboard. The breadboard has accumulated over 2147 hours of various tests with no significant problems.

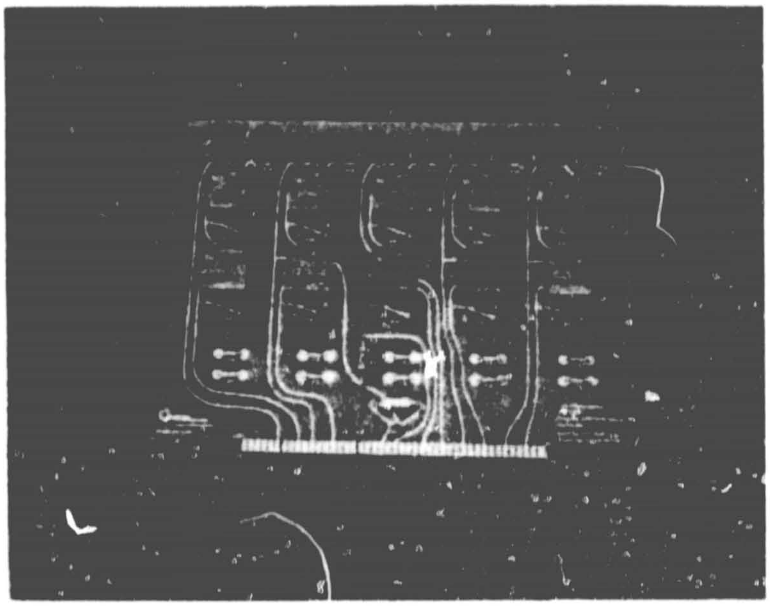
Electronics Assembly Package

A final specification for the fabrication and procurement of an electronic package which includes both the inverter electronics and microcomputer was completed. This package defines the printed circuit PC card requirements, microcomputer chassis fabrication, chassis wiring lists and P.C. card component parts list.

Fabrication of the verification electronics assembly package (including both the inverter and controls logic cards and electronic chassis) was completed. The low-power driver, signal conditioning and microprocessor logic P.C. boards, Figure 56, were successfully bench tested.

Control Logic (Software)

A preliminary software flowchart, outlining the required control loops, was prepared. This flowchart defines the three modes of power plant operation (start-up, run, shutdown) and also describes the sequential, batch, or analog software algorithms associated with each mode. The development of software strategies and programs for each of the control loops was completed. The format used to document the microcomputer software strategies was identical to the format used for the TMS microcomputer -- flowcharts, written descriptions and control schedules describing each control strategy. A software security system to prevent accidential damage or loss of the software files was also instituted. The power plant software consists of 28 routines linked together to form the software program. Table II identifies the required software routines and respective development status.



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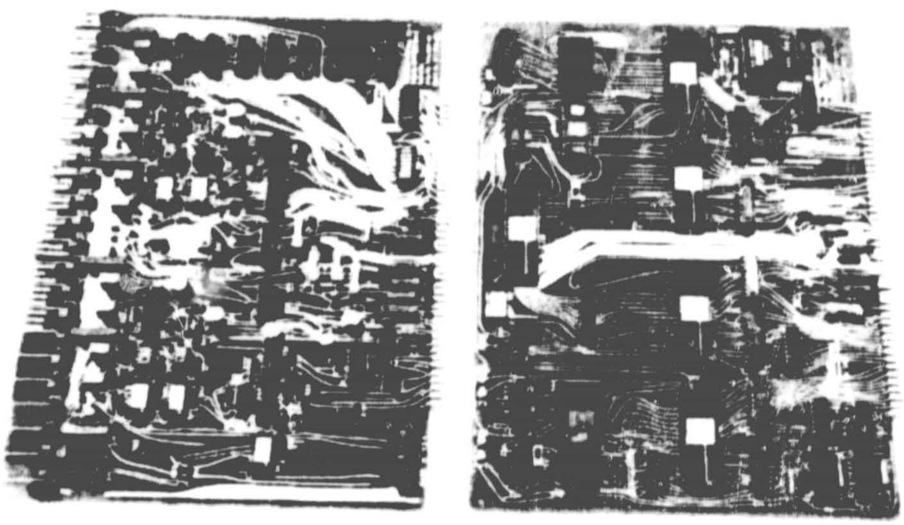


(W-4579)

Figure 56. Printed Circuit Boards

TABLE II. SOFTWARE ROUTINES DEVELOPMENT STATUS

Software Routines	File Name	Written	Edited	Debugged
Initialization	INITL	*	*	*
Start Sequence	STSEQ	*	*	*
Discrete Signal Input	DMUX	*	*	*
Analog Signal Input	AMUX	*	*	*
Start/Run Mode S/D	SRSDR	*	*	*
Timing Control	FARTM	*	*	*
Multiply	MULT	*	*	*
Line Generator	EQNF	*	*	*
Hot Well Temperature Control	TMREG	*	*	*
TMS Heater Control	HTACT	*	*	*
L/G Hex Bypass Control	FLOW	*	*	*
Feedwater Pump/Circulating Pump/Blowdown Sol.	FDBL	*	*	*
Run Mode S/D	RMSD	*	*	*
Condenser Fan Control	CONFR	*	*	*
Powersection Protection	PPROC	*	*	*
Fuel Control	FUEL	*	*	*
Reformer Burner Air Control	RBAVC	*	*	*
Cathode Air Control	CAVC	*	*	*
Coolant Flow Loss Control	CFLOW	*	*	*
Start Shutdown	STSHT	*	*	*
Micro Active Indication	MAFWD	*	*	*
Self Health	SELF	*	*	*
Start Mode to Run Mode Conversion	CONV	*	*	*
Calculate Hotwell Temperature	TMCAL	*	*	*
Stack Conditioning	COND	*	*	*
P/A Programming Support Routine	P/A	*	*	*
I/O Programming Routine	PERIP	*	*	*
Decrement Timers	DECTM	*	*	*

The system flowchart, outlining the sequence of microcomputer tasks, was completed. The system truthtable, describing the different sequential power plant operating states and component status during each state, is shown in Figures 57 and 58.


12-86

Figure 57. Control Logic Flow Chart

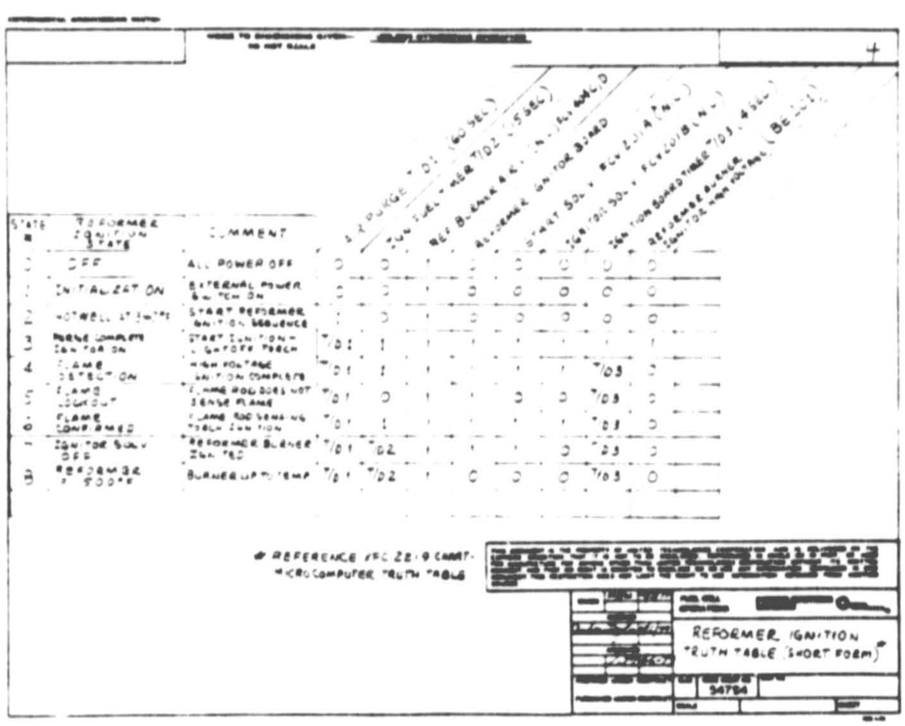

12-87

Figure 58. Control Logic Flow Chart

Power Distribution Center

The design of the power distribution center, Figure 59, was completed on schedule. The design was revised later to include automatic transfer of the power plant components and heaters from external power to inverter power for maintenance of power section temperature during shutdown. A revised design sketch of the control panel was prepared and released for fabrication. The fabrication of the unit, Figure 60, is nearing completion.

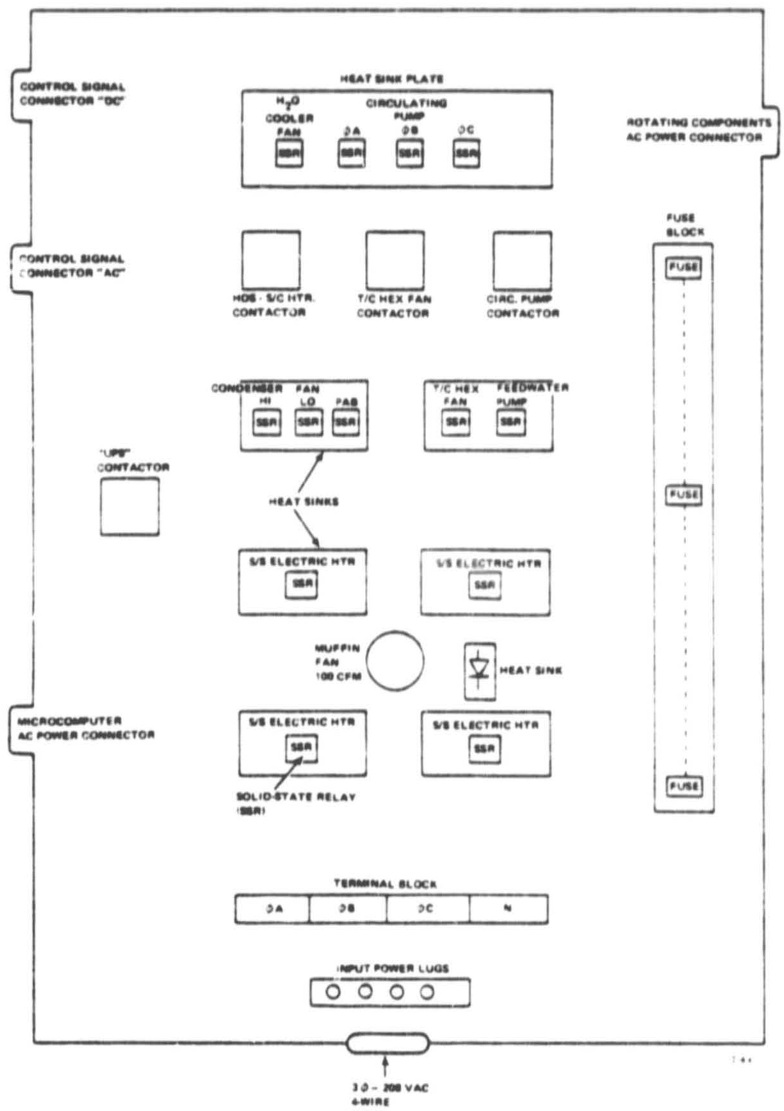
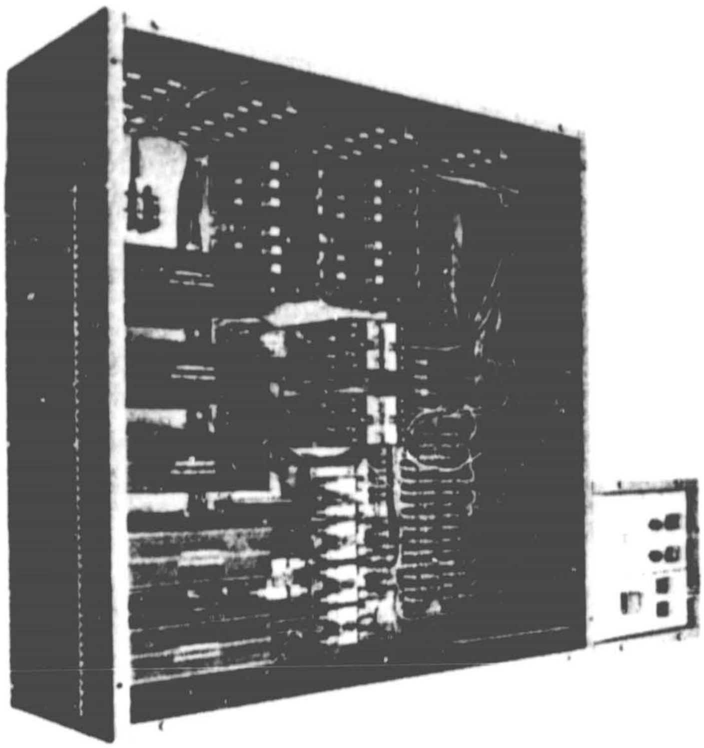


Figure 59. Power Distribution Box



(W-4607)

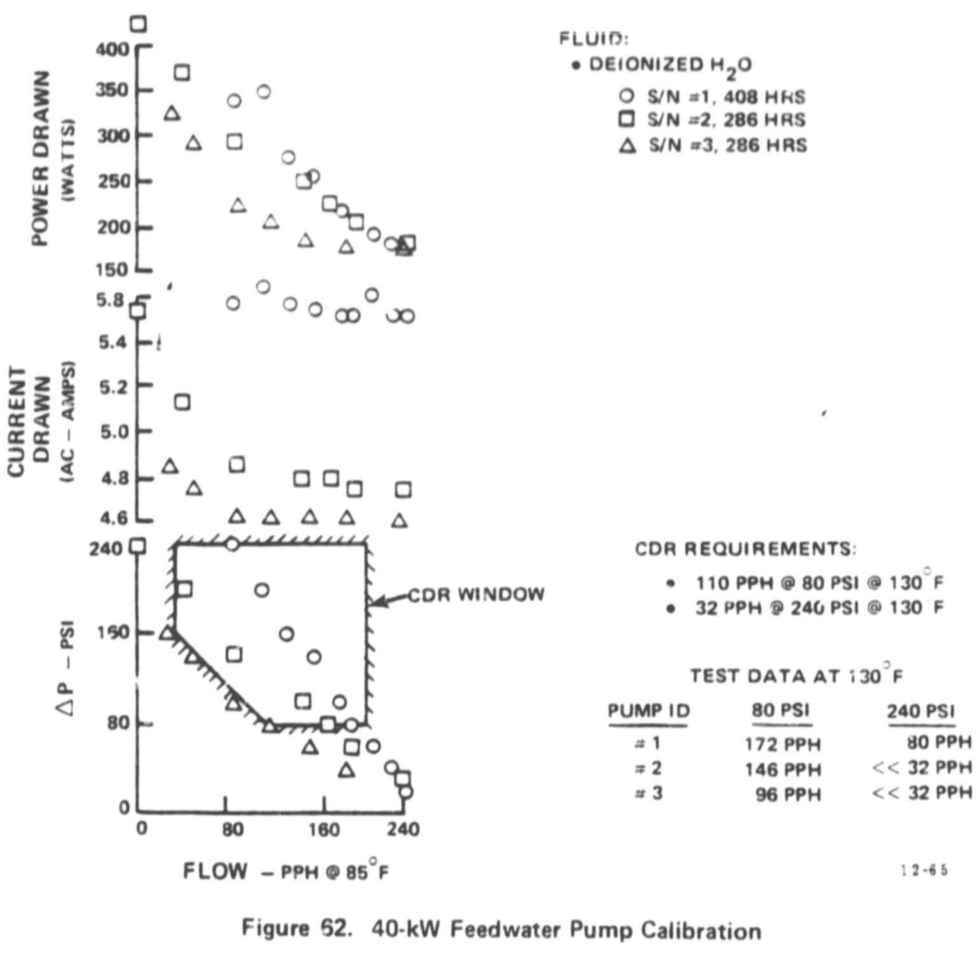
Figure 60. Power Distribution Center

F eedwater Pumps

Initial bench testing of the three small feedwater pumps at 130°F water temperature Figure 61, resulted in the pump characteristics shown in Figure 62. Loss in pump performance with operating time was found to be significantly worse at greater pump operating pressures, Figure 63. Investigation of this problem revealed the presence of contaminants within the rig's water system. The loss in pump performance may have been rig-related. In view of these test results, three additional pumps with larger flow capacity were shown in Figure 64, in which water flow and parasite power were monitored, demonstrated that the larger pumps exceed the CDR water flow. Several approaches to reducing the water flow were investigated. Additional cyclic and endurance testing was conducted wi.h no observable degradation in pump performance. Pump #1 was operated continuously and pumps #2 and #3 were cycled, 5 minutes on - 5 minutes off.

(W-4338)

Figure 61. Feedwater Pump



TEST DATA AT 130°F

PUMP ID	80 PSI	240 PSI
# 1	172 PPH	80 PPH
# 2	146 PPH	<< 32 PPH
# 3	96 PPH	<< 32 PPH

Figure 62. 40-kW Feedwater Pump Calibration

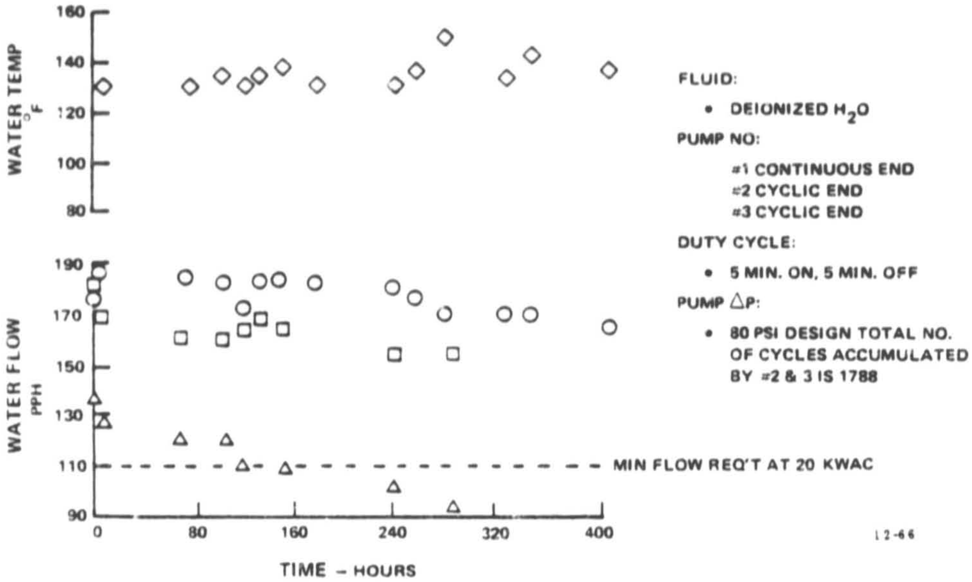


Figure 63. 40-kW Feedwater Pump Endurance Test

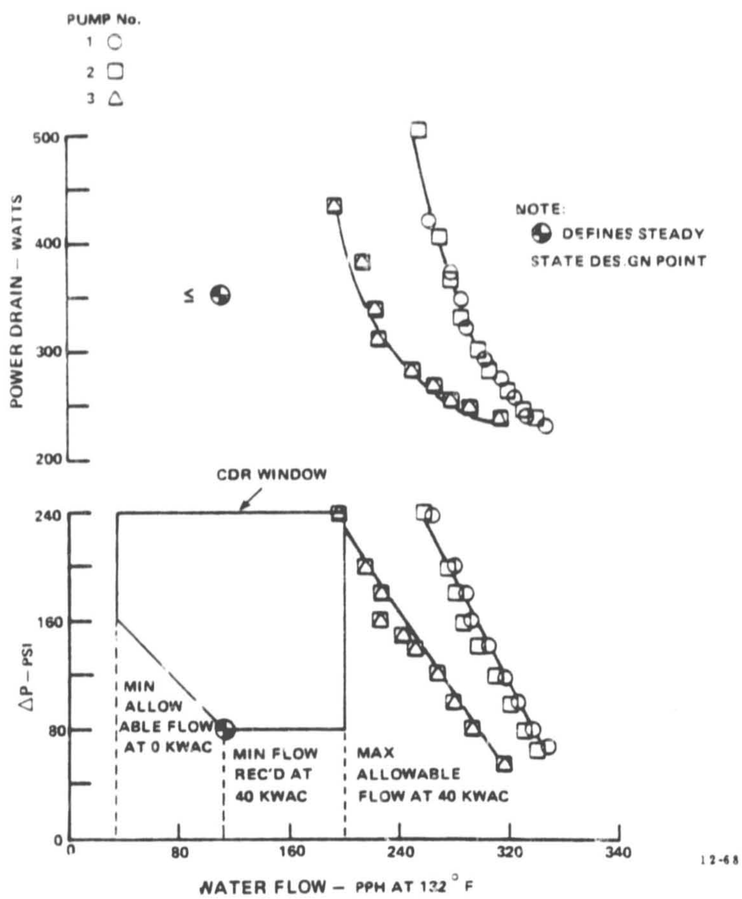


Figure 64. Initial Calibration of Candidate Feedwater Pump

The excessive water flow was considered unacceptable for power plant operation and requires a fixed orifice bypass to meet the CDR. As an alternate approach, the smaller Procon feedwater pumps, ordered for reevaluation, were installed and tested for 425 hours at operating conditions. These pumps satisfied the lower limit of the CDR but provided very little margin for pump performance decay. As a result, the unit with a fixed orifice bypass has been selected. Figure 65 shows pump performance with the optimum bypass flow.

Endurance and cyclic bench testing of the three larger feedwater pumps exceeded the 3000-hour milestone with acceptable performance. Some minor, but manageable, water leakage occurred from the pump seal cavity. Bench testing was continued for an additional 2000 hours to further evaluate the seal leakage. The leakage stopped completely, but testing will be continued to ascertain that seal leakage is not a problem.

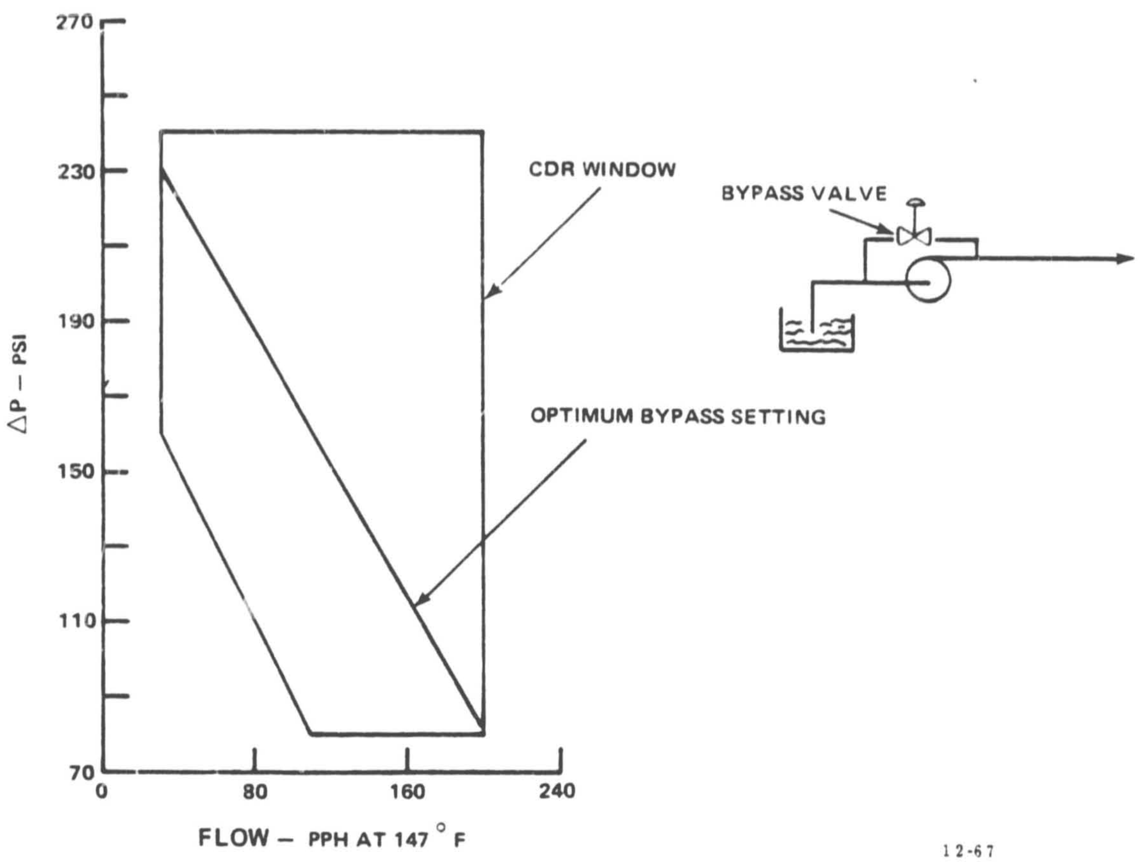


Figure 65. Feedwater Pump Performance

Water Circulating Pump

Performance bench testing of a water circulating pump was completed. Preliminary test results showed that parasite power and performance exceeded CDR allocations, Figure 66. With a trimmed impeller, parasite power is reduced and performance is brought in conformance with the CDR, Figure 67.

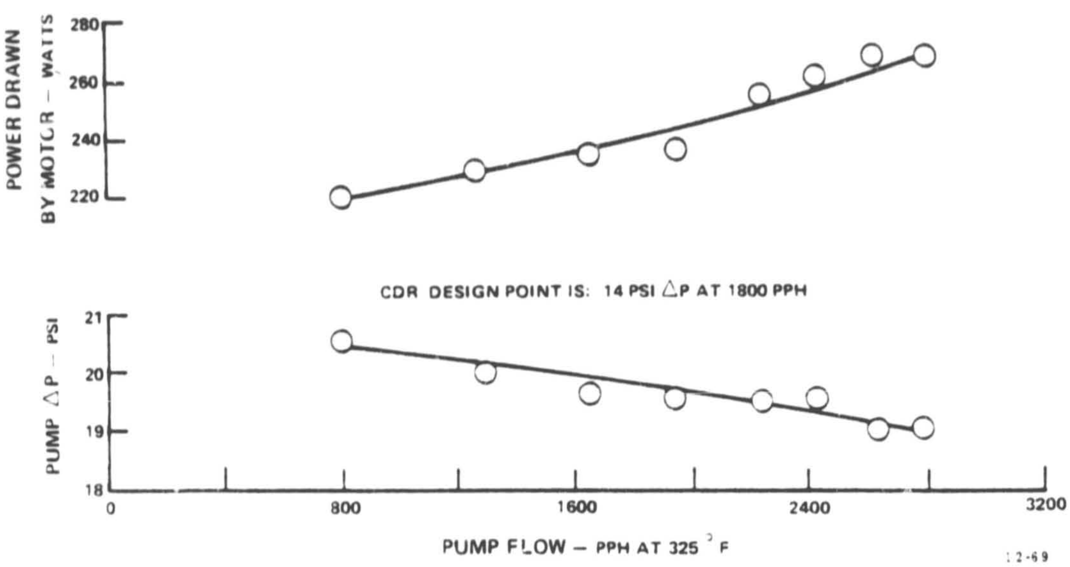


Figure 66. Water Circulating Pump Performance Curve

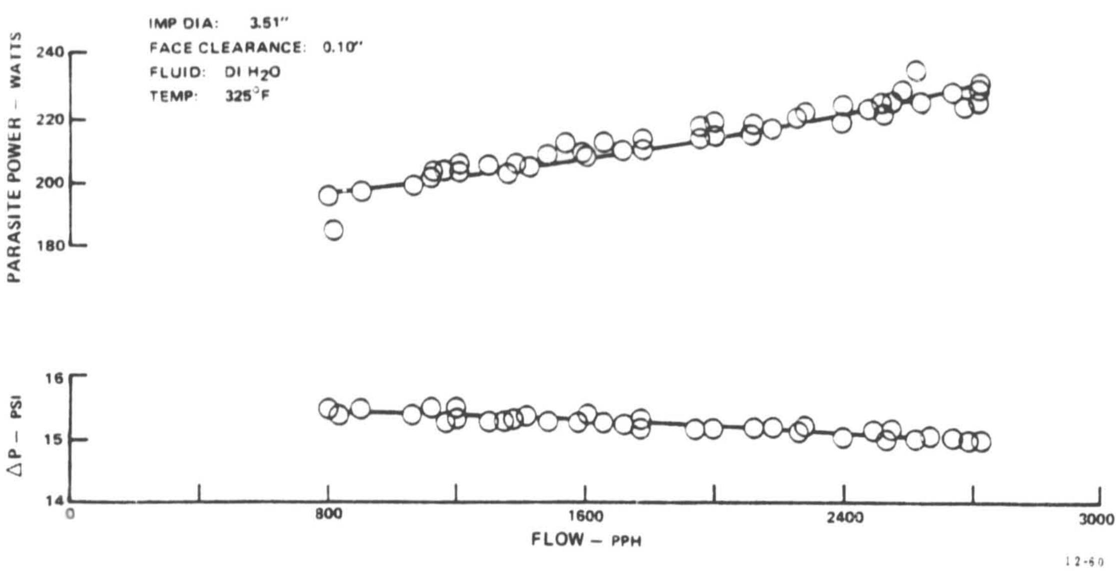


Figure 67. Water Circulating Pump Performance Curve

HDS Vacuum Regulator

Three candidate HDS vacuum regulators were evaluated for high temperature operation. The first unit, Figure 68, was a standard unit already modified for high temperature operation. Performance at 75°F met the component design requirements but at 450°F the results were out of limits, Figure 69. This unit was found to have a damaged metal diaphragm. The manufacturer supplied a substitute elastomer diaphragm. Testing with the diaphragm was successful up to 500°F, Figure 70.

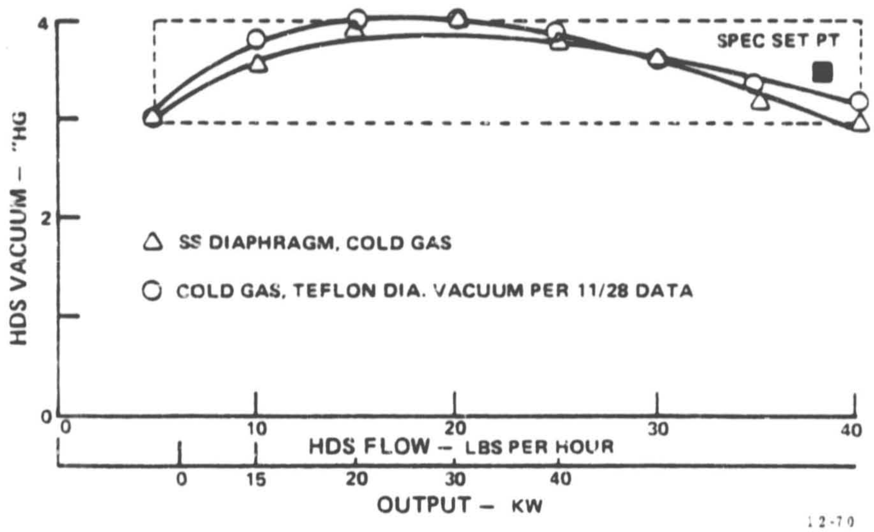


Figure 68.
High Temperature
Performance Curve

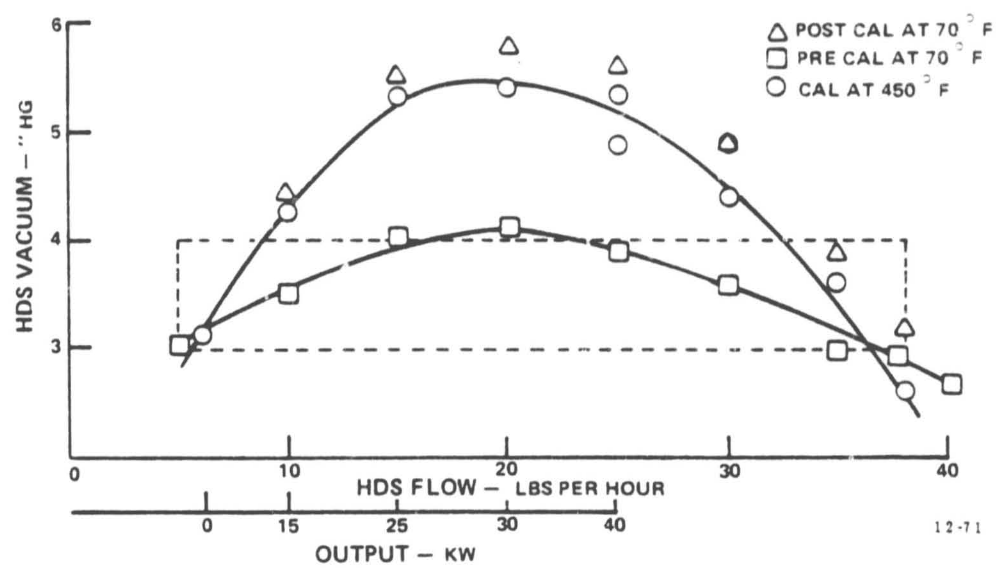


Figure 69.
High Temperature
Performance Curve

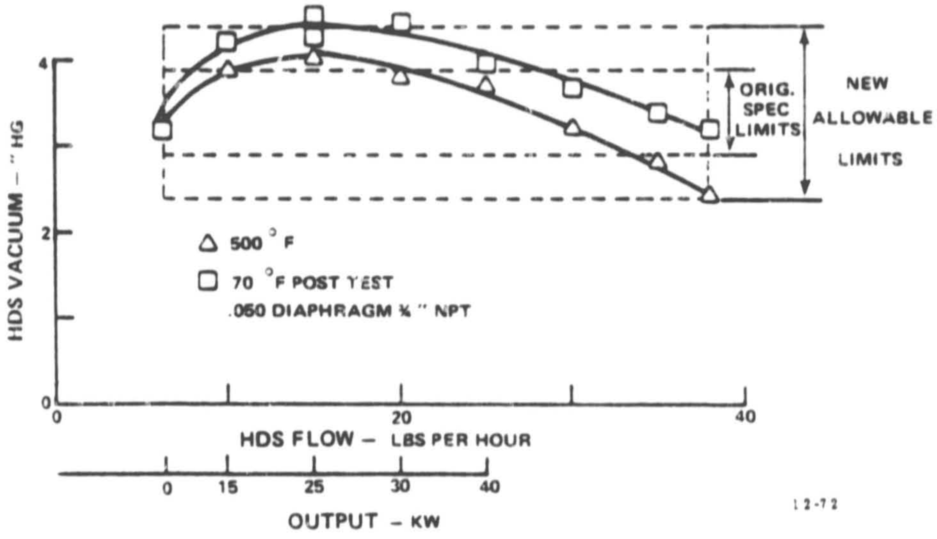


Figure 70. Regulator with Viton Diaphragm

A backpressure regulator was modified by PSD for vacuum pressure operation and bench tested. Testing from 75-500°F shows satisfactory performance, Figure 71. Testing at maximum overflow conditions indicates an increased drop which did not meet the limits. A review of the system requirements resulted in an increased, acceptable operating band. Figure 72 shows that the unit met the new allowable limits and this unit will serve as a backup.

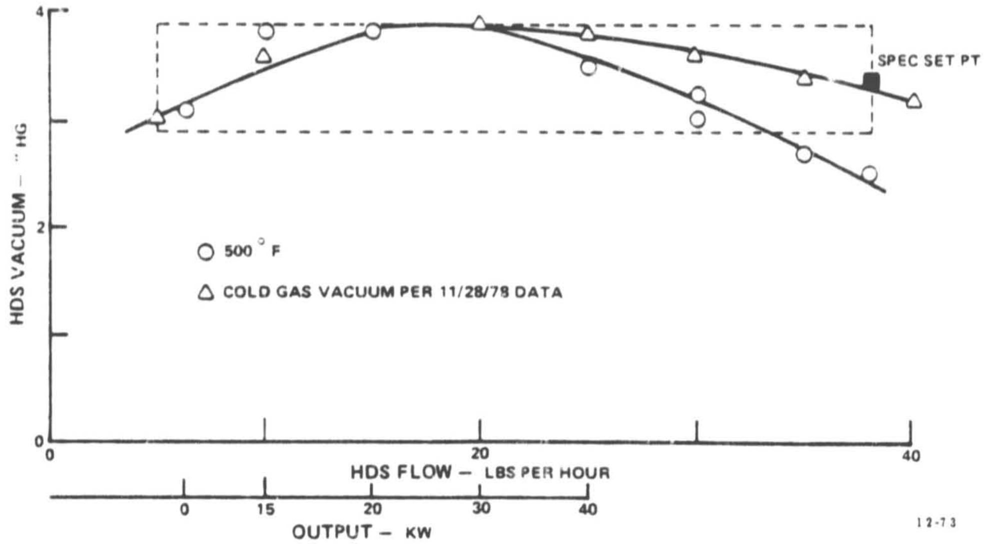


Figure 71. Backpressure Regulator Performance Curve

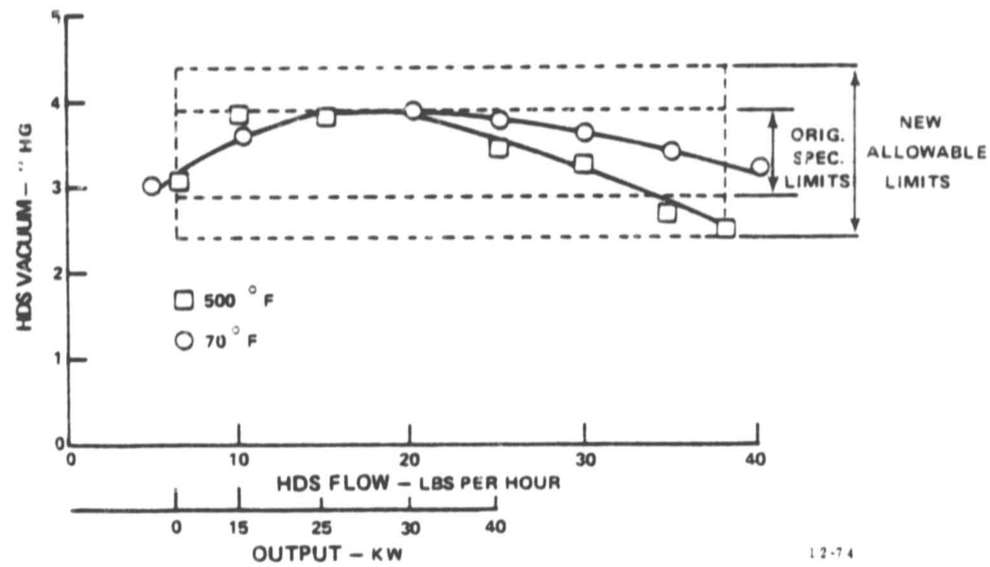


Figure 72. Backpressure Regulator Performance Curve

The third unit, is a standard regulator unit requiring no modification and was the least expensive. Preliminary bench testing of the vacuum regulator at room temperature provided results (Figure 73) that satisfied CDR performance. Additional testing of the regulator included operating the regulator at 50°F above the 475°F design temperature for 8 hours and at design temperature conditions for 25 hours. This unit was selected for the verification power plant.

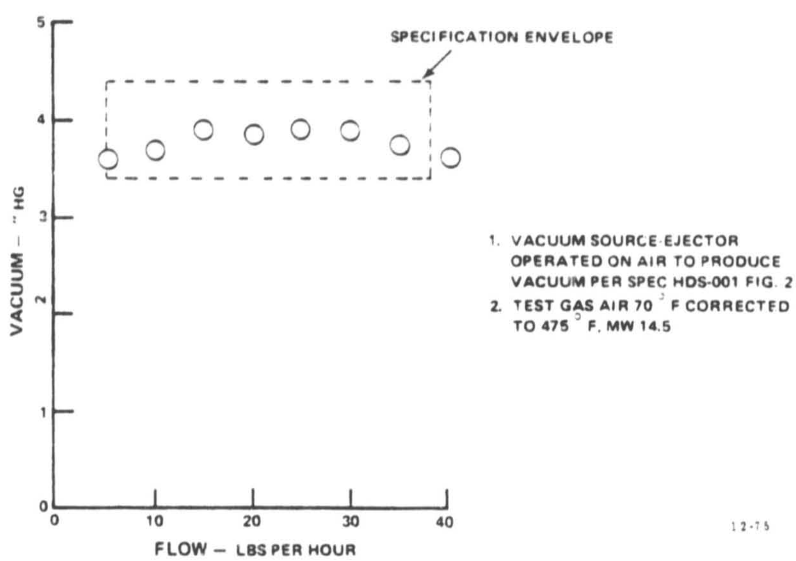


Figure 73. Vacuum Regulator Performance Curve

Condenser and Thermal Control HEX Fans

Performance bench testing of the selected 2-speed condenser fan and thermal control HEX fan, in which air flow and parasite power were monitored, was completed. The results show that both fans operate at approximately 3 to 5% below the CDR air flow but consume less power than allocated, Figures 74 and 75.

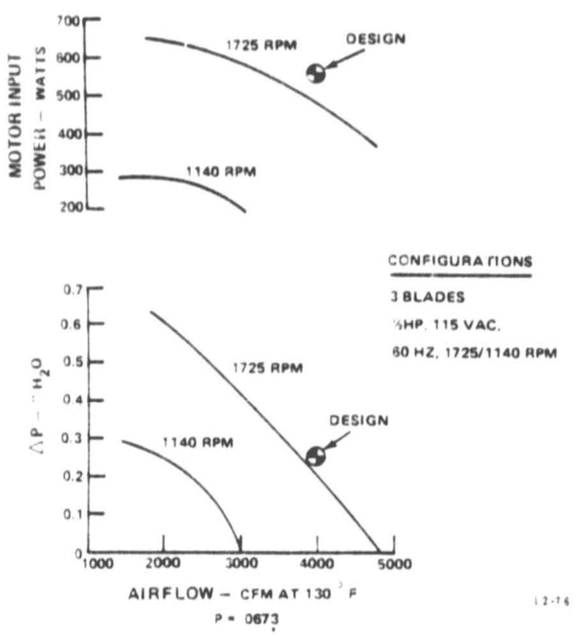


Figure 74. Condenser Fan Performance Curve

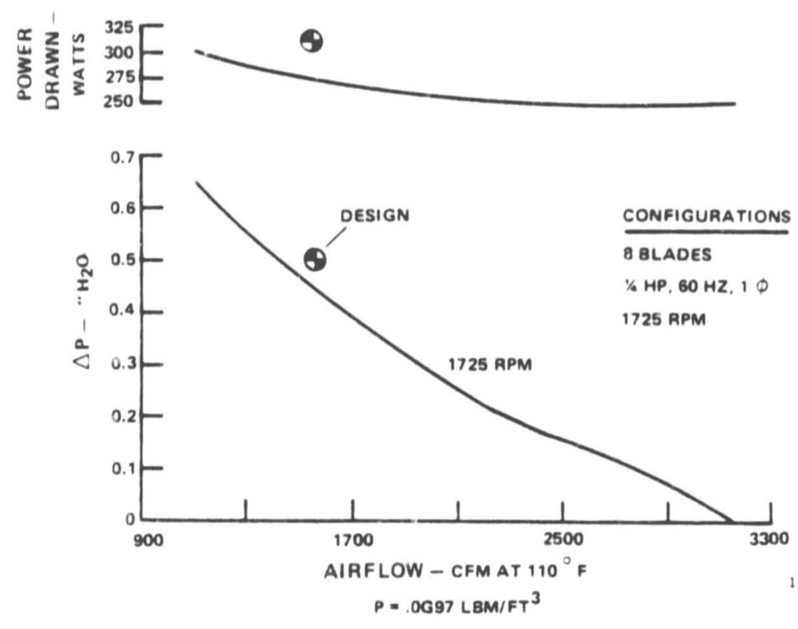


Figure 75.

Thermal Control HEX Fan Performance Curve

Test results of the condenser fan, the HEX fan and feedwater pump parasite power are compared to each CDR allocation in Table III.

TABLE III. PARASITE POWER SUMMARY

Component	Allocated Power	Actual Power	In-rush Current	Steady-State Current
T/C HEX Fan	310 watts	283 watts	21.3 amps/1.8 sec.	4.5 amps
Condenser Fan	550 watts	512 watts	46 amps/.9 sec.	8.3 amps
Feedwater Pump	350 watts	247 watts	42 amps/.1 sec.	5.7 amps

Temperature Switches

Typical control applications for temperature switches include the low-grade HEX bypass valve, cabinet over-temperature detection, and condenser fan operation. The testing of seven candidate switches between 95° and 115°F (with electrical loads applied) is approaching the test goal of 3,000 hours with no shifting of setpoints. Calibration checks have been scheduled every 500 hours.

Valve Actuators

Preliminary testing was started to evaluate the performance of three candidate valve actuators, candidates for controlling the cathode and reformer air, the integrated fuel control and the low grade HEX bypass valve. The water-driven actuators are tested on a cycle rig (3 cycles/min.). After 1320 hours (300,000 cycles) one actuator failed. Disassembly of the actuator showed corrosion of the aluminum parts and carbon steel springs. The manufacturer is supplying two modified units incorporating changes to eliminate the corrosion. The second actuator failed after 1924 hours. The failure was also caused by extensive erosion of the aluminum and carbon steel parts. A smaller lower-cost actuator using the same rolling diaphragm concept and the new corrosion resistant actuator are being cyclic endurance tested.

Endurance testing of the valve actuators continues with no mechanical or leakage problems. Total test time as of 8 June 1979 is shown below:

	Hours	Cycles
Vendor 1	2,057	484,543
Vendor 2 Unit 1	1,224	311,147
Vendor 2, Unit 2	1,800	425,000
Vendor 2, Unit 3, 4, 5	1,122	290,675

The rolling diaphragm unit continues to show better reliability and has been selected for the verification power plant air control valve actuation.

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Design Verification of the Power Plant

Subtask 1.2.5 Thermal and Water Management Subsystem

> The thermal management subsystem rig was operated to provide information for the design of the thermal and water management component subsystem. Engineering specifications covering the thermal and water management subsystem were prepared and used to solicit candidate components from vendors. Verification testing of some of these candidates resulted in the selection of the components for the verification power plant. Harrison Radiator Division of General Motors was selected to fabricate all of the heat exchangers except the condensate preheater, which will be fabricated in-house.

A simplified schematic showing the power plant heat rejection and external heat recovery approach is shown in Figure 76. A heat exchanger and a condenser are provided for customer heat removal of up to 150,000 BTU/Hr through one or two water loops. Excess heat, not removed by the customer, will be removed automatically by air cooled secondary heat exchangers.

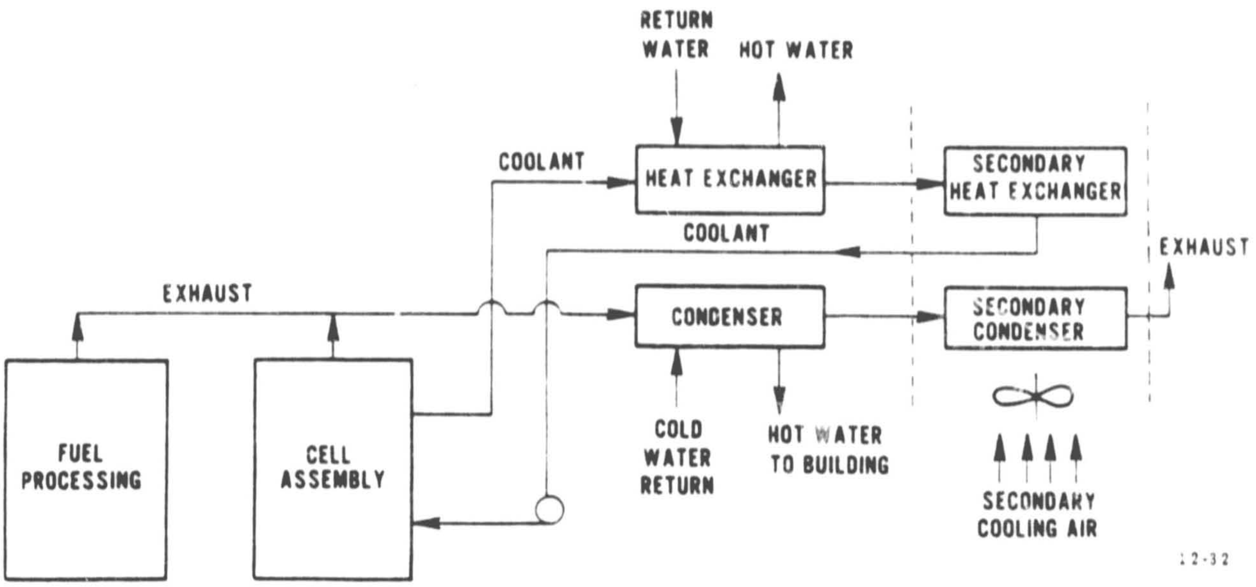


Figure 76. 40-kW Power Plant Heat Recovery Schematic

During this reporting period the thermal and water management subsystem design and development objectives included the continued testing of the thermal management rig, the completion of the design along with the verification of the design by computer models, and the initiation of procurement and fabrication of components. Specific goals included:

- Complete the development testing of the thermal management rig to obtain design data to support design activities.
- Complete the AiResearch design study and evaluate the results for impact on heat exchanger specifications.
- Complete the preparation of the component design requirements and the engineering specifications for the thermal and water management components.
- Inititate procurement of elements and components of the thermal and water management subsystem required for development and the verification power plant.
- Initiate testing of some of the thermal and water management components.

Water Treatment Activities

The design verification testing of the water treatment subsystem on the thermal management rig, Figure 77, was completed. The rig schematic is shown in Figure 78. The rig was operated at zero net, 30 KW, and 40 KW simulated power levels. The analysis of water samples taken from various rig locations verified the successful performance of the individual water treatment components. Figure 79 shows these results at rated 60 KW conditions. The ability of the subsystem to achieve the 2000 hour demineralizer design service life was demonstrate when the water tank/deaerator reduced the condensate CO_2 level from the anticipated 155 ppm level to less than 5 ppm. A longer service life, perhaps consistent with a 4000 hour period, may be possible; however, confirmation of this must await results of actual power plant operation.

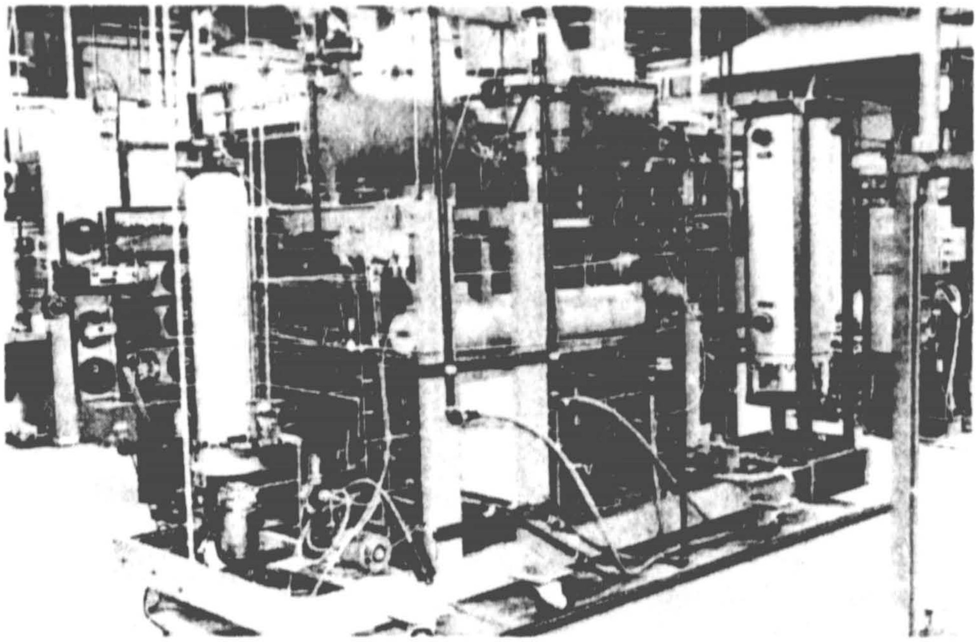


Figure 77. 40-kW Thermal Management Test Rig

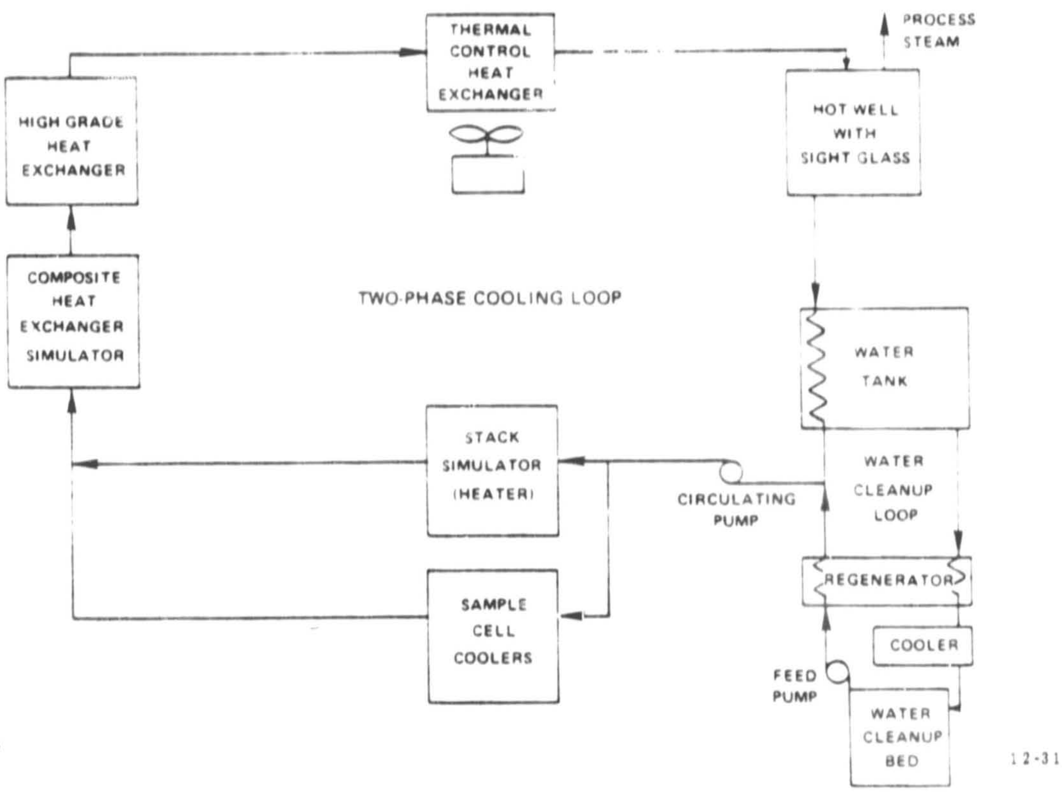


Figure 78. 40-kW Thermal Management Test Rig

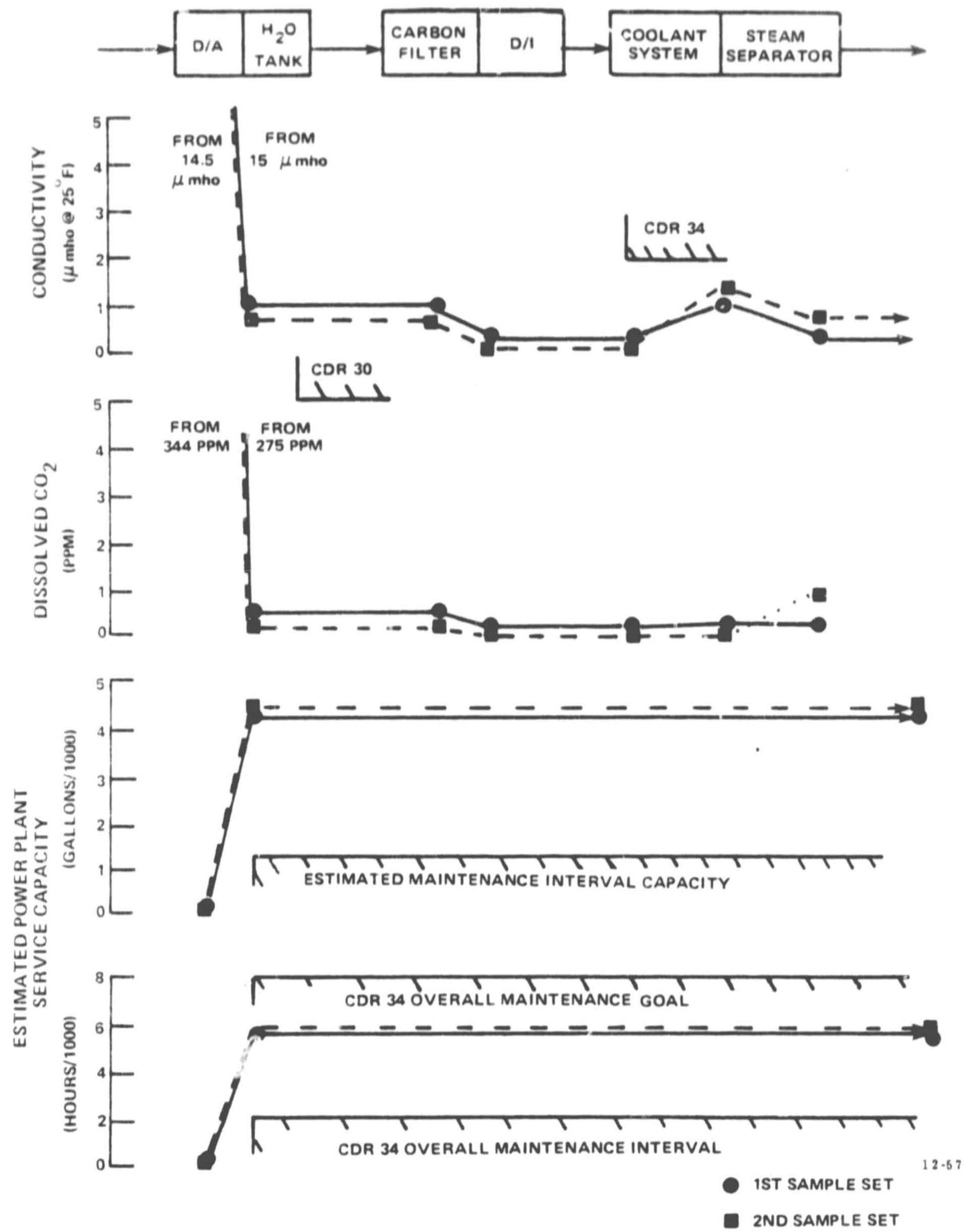
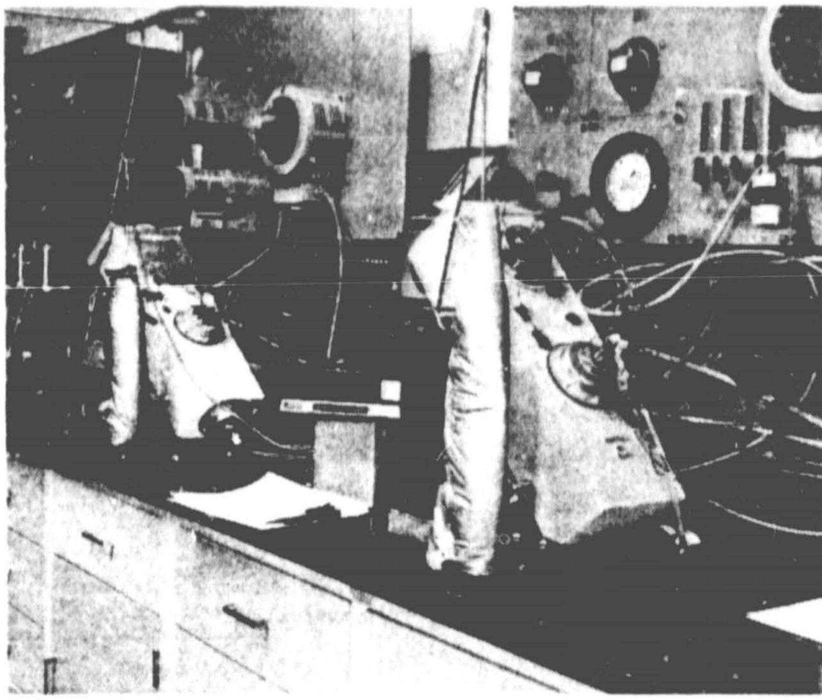


Figure 79. 40-kW Onsite Power Plant WTS Performance

Preliminary specifications for the various water treatment components were submitted to a number of potential suppliers to encourage their participation in searching for low cost suitable components. As a result of the inputs received and testing of two plastic water tank materials, Figure 80, the water treatment specifications were finalized and orders placed for the verification power plant components -- the water tank, demineralizer, charcoal filter, magnetic filter and deaerator. Most of these components are standard commercial products presently marketed and serviced by the suppliers.



(WCN-6739)

Figure 80. Water Tank Testing

Thermal Management Activities

The heat exchanger core and configuration study contract that was initiated with AiResearch during Phase I was completed. The resulting heat exchange functions required for the 40-kW power plant are shown in Table IV . AiResearch recommendations for twelve of the fourteen heat exchanger functions were; (1) plate-fin concept heat exchangers for eight functions, (2) shell and tube for two, (3) fin and tube for one, and (4) tube bundle for one. Integration into a single plate fin

heat exchanger was recommended for the four fuel processing functions (201, 202, 203 and 204); however, increased preoxidizer temperature prevented the integration of HEX 201 with HEX's 202, 203, and 204. Functions 205 and 206 were also integrated.

TABLE IV. 40-kW ON-SITE HEAT EXCHANGE FUNCTIONS

HEX 201	-	Preoxidizer Heater	
HEX 202	-	Preoxidizer Cooler	Integrated to single heat exchanger
HEX 203	-	Shift Converter Precooler	
HEX 204	-	Anode Precooler	
HEX 205	-	Air Preheater	Integrated to single heat exchanger
HEX 206	-	Fuel Preheater	
HEX 307	-	High Grade Heat Exchanger	
HEX 308	-	Thermal Control Heat Exchanger	
HEX 409	-	Regenerator	
HEX 410	-	Water Cooler	
HEX 411	-	Condensate Preheater (PSD Design)	
HEX 312	-	Super Heater	
HEX 513	-	Low Grade Heat Exchanger	
HEX 514	-	Condenser	

Specifications were prepared and requests for quotations were sent to six suppliers. AiResearch Division of Garrett Corporation and Harrison Radiator Division of General Motors provided quotations. After a thorough review of design approaches prepared by both AiResearch and Harrison, purchase orders were placed for all the vendor designed heat exchangers with Harrison Radiator Division.

Gas utility field test participants advised that a hot water high grade heat exchanger was preferred to one using steam. This change was authorized by DOE/GRI and the vendor was instructed to switch his efforts to a water version. Successful completion of the design reviews has placed the vendor in a position to complete the manufacturing activity in September, 1979.

Because the condensate preheater heat exchanger (411) must not only transfer heat to the condensate for degasification purposes but also the materials should be able to withstand or minimize acid attack while performing the mechanics of removing condensed acid, it was decided to design the unit in-house and to conduct a supportive test program. The test program consists of running units incorporating the candidate concepts downstream of a 24-cell stack rig. Outlined below are the concepts evaluated and a statement regarding the supportive design information sought:

- o "Sacrificial" stainless steel shell and tube -- determine the corrosion rate, acid removal capability and life cycle cost of a low cost design.

- o All-Teflon shell and tube -- determine the degree of baffling required, corrosion rate, and acid removal capability.

- o Coated metal formed plate -- determine the acid removal capability.

All three units were designed, built and tested. The sacrificial shell and tube and the Teflon tube bundle failed to remove sufficient acid (60 - 75% effectiveness); however, the plastic coated formed plate exhibited satisfactory acid removal (90 - 93% effectiveness).

Because vendor quotes for coated ripple plate were unacceptable, an alternate coated metal bar-plate configuration was designed by PSD, and steps taken to manufacture this component.

A vendor was selected for the hot-well separator (SEP 321). The election was made primarily on the basis of the vendor's proposed configuration. Other configurations would have required extensive rearrangement of the power plant components to accommodate their design. The design review of the vendor's design was acceptable and fabrication is in process.

3.0 CONTRACT TASKS

Task 1.0 Definition, Design and Design Verification of the 40-kW Power Plant

Subtask 1.2 Design and Design Verification of the Power Plant

Subtask 1.2.6 Verification Power Plant

> The conceptual arrangement of the power plant was established with the help of a hard mockup of the power plant. The mockup includes all major power plant subsystems and components, the plumbing, thermal isolation compartments, and the wiring harness. The power plant has been arranged into three thermally isolated compartments.
>
> The base frame and support structure for the verification power plant has been fabricated. This frame will accommodate all normal handling and shipping loads. Process planning, detail drawings, and quality control requirements for power plant assembly are being defined. Verification test plan activities were started. Design of the power plant test stand was initiated.

The conceptual arrangement of the power plant was completed. The size of major components was defined and interface control drawings prepared. The fuel processing components and the steam separator are located in a thermally isolated compartment to maximize thermal efficiency and safety. The water treatment resin beds and charcoal filter are also located in a separate thermally isolated compartment to maintain allowable temperature range (33° - 140°F). A majority of the mechanical controls are located in one area to enhance maintainability. Design layouts were completed which reflect the packaging arrangement. The general arrangement of the various power plant components is shown in Figure 81.

A full size mock up of the power plant was fabricated. The mockup was used to verify the final packaging arrangement. The mockup depicts all major power plant components, the large plumbing, thermal isolation compartments, and wiring harness. Figures 82 and 83 depict the power plant mockup.

The power plant base frame was designed. The base is composed of rectangular steel tubing having a cross section 4 inches by 8 inches. The base design is compatible with all normal handling and shipping loads including lifting at one corner.

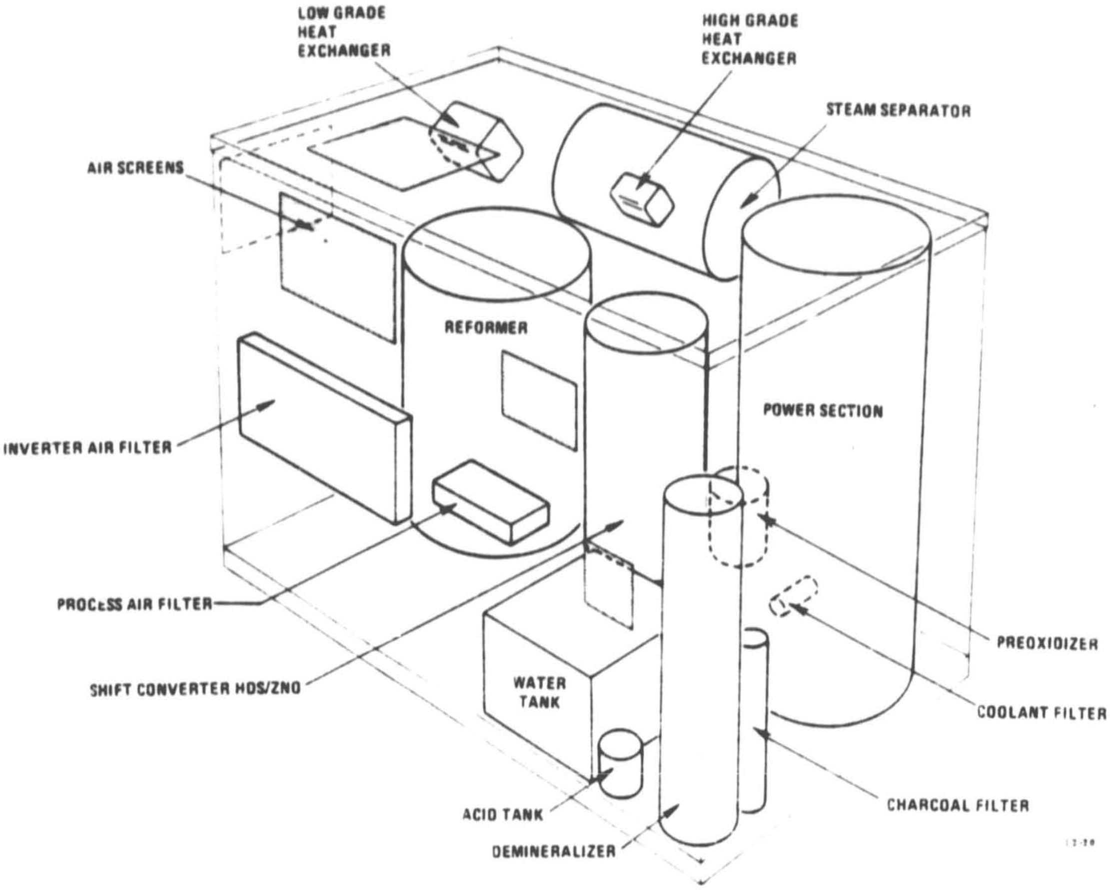


Figure 81. General Arrangement of 40-kW Power Plant

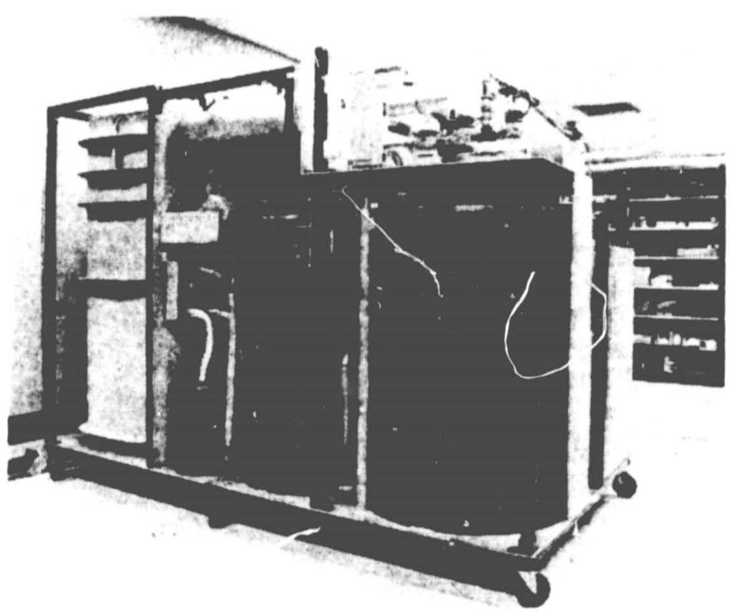


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Figure 82. 40-kW Verification Power Plant Mock-Up

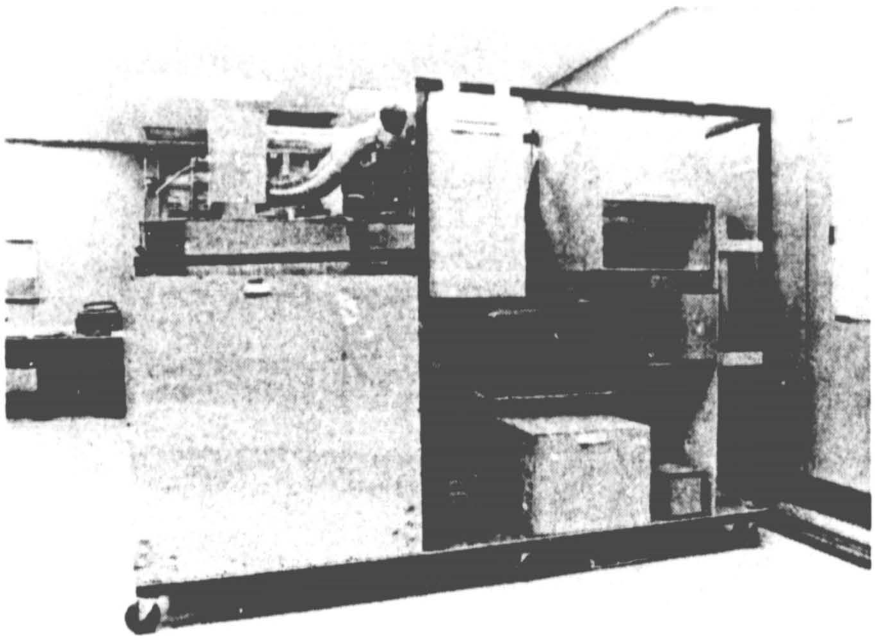

Figure 83. 40-kW Verification Power Plant Mock-Up

The power plant support structure was defined and analyzed for deflections under shipping loads. The structure will be rigid enoug' to prevent the power section from experiencing any excessive stresses during shipping. The design of the power section restraint will accommodate the dimensional tolerance that will be encountered during assembly. The power plant plumbing was designed and piping loads and pressure drops were calculated. Detail drawings were completed.

Verification power plant assembly procedures were written. Inspection and quality control requirements were defined for the power section and fuel processing subsystem.

Verification test activities were initiated. Procurement of hardware and plumbing for the verification power plant was initiated, and the power plant base was fabricated. Fabrication of the condenser box and thermal control heat exchanger/fan/louver assembly has begun. Design of the verification power plant test stand was started. A draft of the verification test plan has been prepared. The plan includes the tests and other verification techniques to be used by the contractor in confirming that the 40-kW verification power plant meets the requirements of the 40 kW Model Specification No. FCS 1460.

3.0 CONTRACT TASKS

Task 2.0 Pilot 40-kW Fuel Cell Power Plant (FCP) Operation

> Testing of the pilot 40-kW power plant, originally built and run as part of the TARGET gas industry program, was completed. This power plant has continued to provide performance, durability and other design requirements data needed for optimizing the 40-kW power plant configuration. At the end of the planned testing program, the pilot power plant exceeded 18,000 hours of on-load operation, with over 2800 hours of testing with the latest power section. Operation included a continuous run of over 3000 hours, successful checkout and operation of a microprocessor based electronic control package and repeated demonstration of 38-40% electric generating efficiency and 80% overall fuel utilization while simulating energy supply for a 16 unit apartment.

The pilot 40-kW power plant was built during the TARGET program as the first of a family of on-site power plants. This development power plant established the technical feasibility of on-site fuel cell power plants:

- low emissions
- 40% electric generating efficiency
- operation from 0 to 52kW
- load following
- high quality power
- instant load response
- up to 80% fuel utilization with heat recovery

The objective of operating the pilot 40-kW power plant under this contract was to provide engineering design requirements data, component durability and performance information, to verify several control and thermal management concepts and to obtain experience operating heat pumps and heat recovery equipment.

The power plant was installed in an area designed to permit long term unattended operation while powering typical simulated residential and commercial electric and thermal loads such as domestic hot water tank, building lighting, electric heat pumps, absorption air conditioner and a portion of the building computer system. The fuel cell and some of this energy equipment is shown in Figure 84.

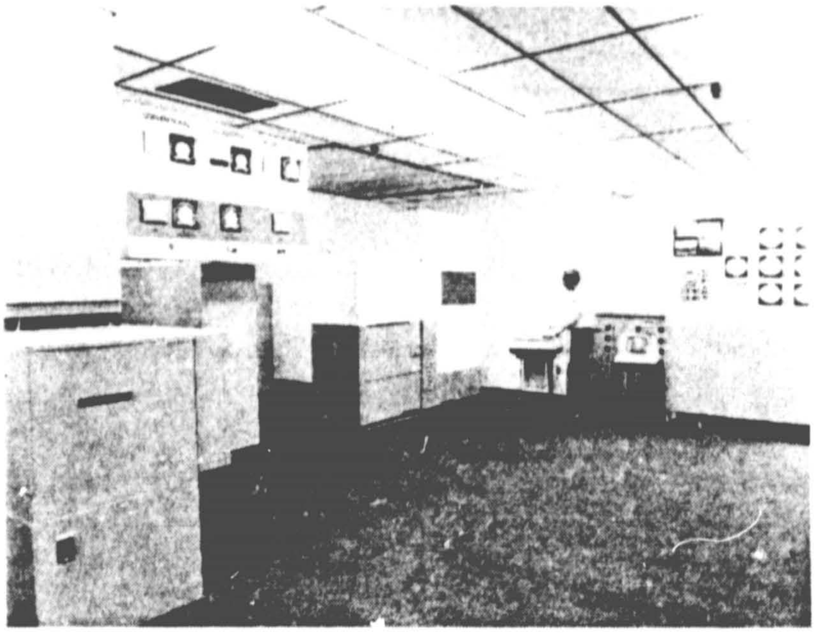

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Figure 84. Power Plant Equipment Demonstration Room

During the Phase I, engineering and development effort that ended on June 30, 1978, the power section accumulated nearly 8300 hours of operation including a continuous run of over 3000 hours. The reformer has accumulated nearly 16,400 hours of successful operation. During the last 4,200 hours, power plant control logic was furnished by a microprocessor based control of the configuration planned for the prototype power plant.

The planned pilot power plant test program was completed in early June 1979 as scheduled, and the operational highlights of the power plant over its four years operational history is summarized in Table V. Overall system efficiency at shutdown was 37.8% at 25-kW net.

Operation of the pilot 40-kW power plant provided design and durability data of great value in designing the 40-kW field test power plant. Component endurance in the power plant environment was very significant, Table VI, and has contributed greatly to the choice of prototype ancillaries.

TABLE V. PC18 PILOT POWER PLANT HIGHLIGHTS

- BUILD 4 DEMONSTRATED OVER 8,000 HOURS WITH ONE STACK ASSEMBLY, OPERATING CONTINOUSLY FOR OVER 3,000 HOURS.
- RELIABILITY OF 40-kW MICROPROCESSOR DESIGN DEMONSTRATED.
- LOW FUEL PROCESSING EFFICIENCY DECAY OF 3% DEMONSTRATED OVER 18,000 HOURS OF OPERATION.
- SHUT-DOWN CONDITIONS ANALYZED FOR FIELD TEST DESIGN.
- INVERTER COMPONENTS SUBJECTED TO REALISTIC FIELD TYPE OPERATION FOR 18,000 HOURS.
- FAILURE DATA ON COMPONENTS FED INTO 40-kW DESIGN.

TABLE VI. PC18 PILOT POWER PLANT
COMPONENT ENDURANCE THROUGH JUNE 15, 1979

	HOURS
AIR AND FUEL CONTROLS	18,023
SHIFT CONVERTER AND ANODE PRECOOLERS	18,363
SOLENOID VALVES	11,217
COOLANT PUMP AND ACCUMULATOR	11,218
WATER TANK PRECOOLER	9,931 A
CONDENSERS	9,931 A
COOLING FAN	12,802
INVERTER	16,382
WATER PUMP	7,046 A
BOILER	15,909
REFORMER	16,393
FUEL CELL ASSEMBLY	8,293 A
MICROPROCESSOR ELECTRONIC CONTROL PACKAGE	4,247

A - LONG TIME COMPONENTS NOT IN PRESENT BUILD

As a result of the pilot power plant test experience it was concluded that:

- o A reliable on-site fuel cell power plant can be developed.
- o Dielectric coolant is inappropriate for power plant use, due to incompatibility with the power section catalyst.
- o The small amount of electrolyte in the power section exhaust must be reduced further to protect downstream components from corrosion.

The last two conclusions have been addressed in the field test power plant design by using two phase water cooling and by adding an acid condenser to the cathode exhaust.

Tests were conducted to determine if air would backflow into the shift converter catalyst bed after a shut down when passivation gas was not used. Although the presence of air was detected, the extent of catalyst oxidation was not determined. A catalyst reduction test was therefore conducted and a mild exotherm was observed when hydrogen was introduced into the shift converter. The analysis of the test results showed that the amount of catalyst oxidation was slight and that unpassivated shut downs, as planned for the on-site power plant, can be accomplished without adverse effect on the shift converter.

After 8300 hours of Build 4 operation the power plant was overhauled. To obtain design information relative to power plant endurance, the reformer was opened and inspected to determine its condition after 13,000 hours of operation. The overall condition was considered good. A flow check of the reformer catalyst bed was completed. The pressure drop was essentially unchanged after 13,000 hours of operation indicating no carbon plugging and no catalyst pellet break-up. Figure 85 shows the overall good condition of the reformer tubes and Figure 86 reflects the satisfactory condition of the reformer burner.

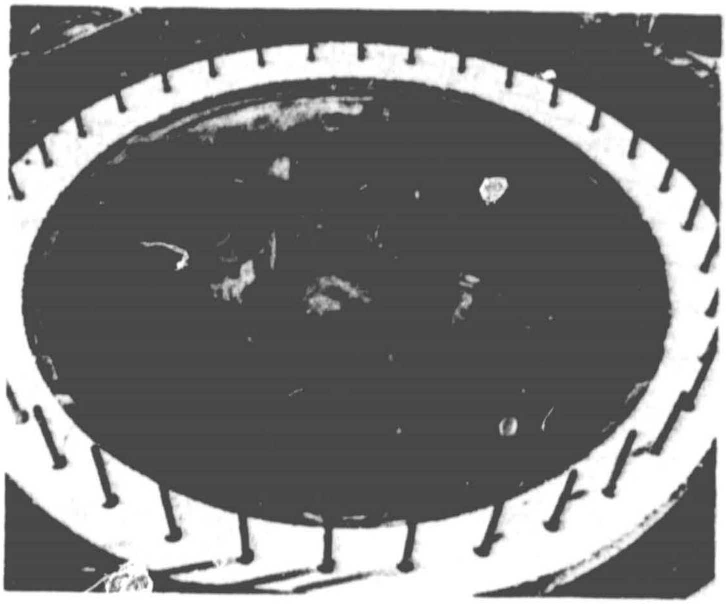

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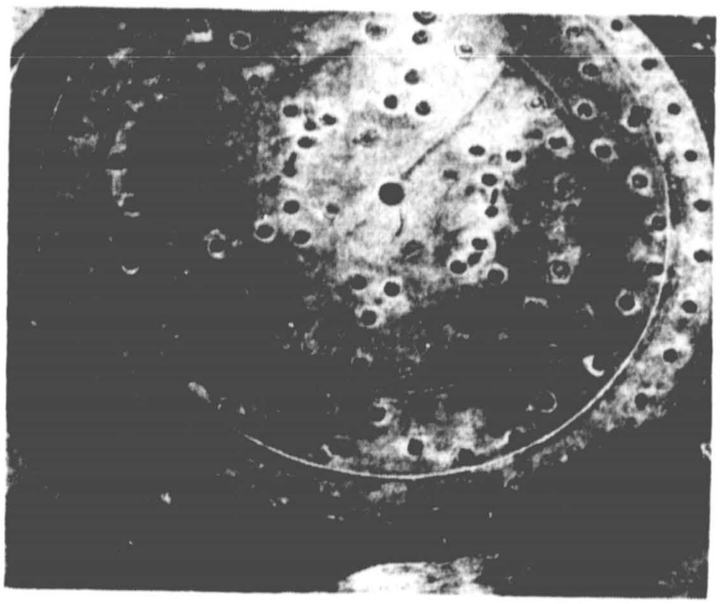
Figure 85. Pilot 40-kW Reformer of 13,045 Power Plant Hours After Cleanup



W-6366A)

Figure 86. X-626-4 Reformer Burner Start Fuel Jet at 13,045 Power Plant Hours After Cleanup

A replacement stack similar to the previous stack configuration was installed. The low grade heat exchanger and one of the exhaust condensers were also replaced in the thermal management system. The existing heat exchangers failed due to acid corrosion.

The power plant was restarted and put into endurance operation. Numerous minor problems caused several power plant shutdowns, but the power plant was operated over the full power range to 40-kW and the cell stack performance was equal to the best performance of any previous power section.

The pilot 40-kW power plant was repeatedly operated as part of an on-site total energy system to demonstrate high fuel utilization in a simulated 16 unit apartment. The fuel cell system consisted of a fuel cell providing electricity for the building and to drive a heat pump, hot water and by-product heat for space heating and domestic hot water. A traditional energy system employing a gas furnace and central station electricity and an all-electric system using central station electricity for heat pumps and supplemental resistance heat and building electricity were also demonstrated or simulated. Schematics of these three systems are shown in Figure 87.

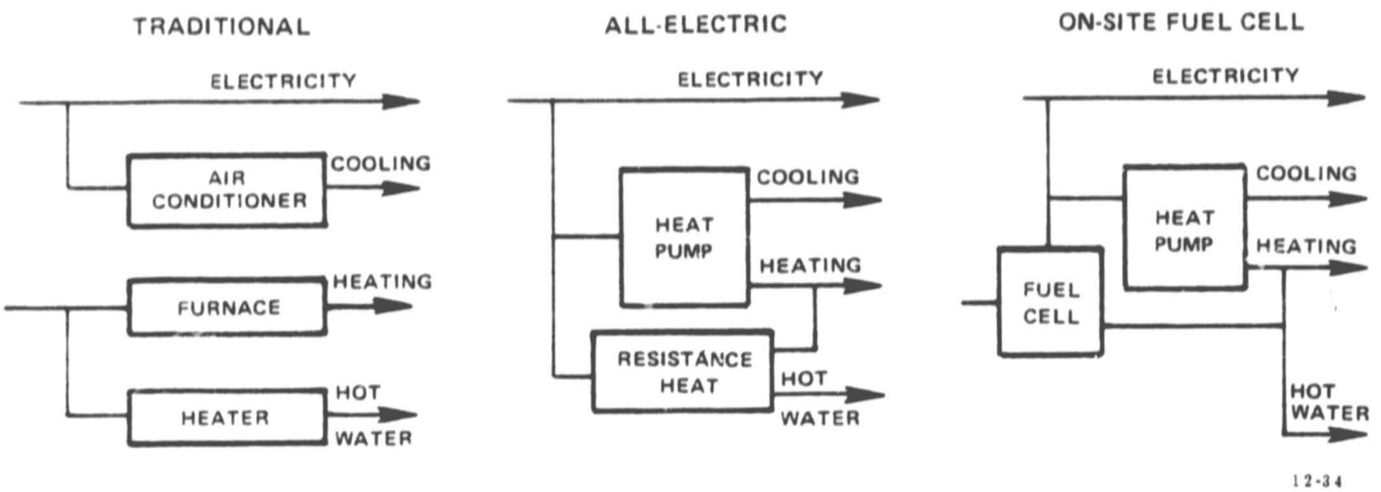


Figure 87. Comparison of Three Systems

The fuel energy resources for all three systems were measured or simulated for a typical winter day in Hartford. Substantial fuel savings are possible with a fuel cell energy system, Table VII. This example also shows that the fuel cell used less gas in providing both electricity and heat than was used in the conventional system to provide heat alone. A complete test history of the pilot 40-kW power plant is shown in Table VIII. Builds 1,2 and 3 were tested in the TARGET era.

Build 4 was tested during Phase 1 of this contract; build 5 was tested during this reporting period.

TABLE VII – 16 UNIT APARTMENT EXAMPLE IN HARTFORD, CONNECTICUT

REPRESENTATIVE WINTER DAY	TRADITIONAL	ALL ELECTRIC	ON-SITE FUEL CELL
USEFUL ENERGY			
TOTAL – BTU/HOUR	330,000	330,000	330,000
HEAT – BTU/HOUR	290,000	290,000	290,000
ELECTRICITY – KW	10.0	10.0	10.0
METERED ENERGY			
FUEL – BTU/HOUR	380,000	-----	320,000
ELECTRICITY – KW	10.0	74.0	-----
ENERGY RESOURCES REQUIRED			
TOTAL – BTU/HOUR	480,000	740,000	320,000

TABLE VIII. PC18 PILOT POWER PLANT TEST HISTORY

BUILD	1	2	3	4	5
TEST PERIOD	MAY 1975 OCT. 1975	DEC. 1975 SEPT. 1976	NOV. 1976 MAR. 1977	APR. 1977 JUNE 1978	NOV. 1978 JULY 1979
MAXIMUM POWER, kW	47	52	OVER 40	OVER 40	OVER 40
MAXIMUM ELECTRICAL EFFICIENCY, %	39	40	37	39.7	39.5
TEST TIME, HOURS	2,138	3,107	1,638	8,293	2,823
CUMULATIVE TEST TIME-HOURS	2,138	5,245	6,883	15,176	18,023

3.0 CONTRACT TASKS

Task 3.0 Fuel Cell Technology

Completed

Task 4.0 Program Management, Planning and Review

During this annual reporting period, the contractor has submitted monthly technical status, cost management, milestone, and contract management reports. In addition, oral technical reviews were held for representatives of DOE, NASA, and GRI, every 2-3 months at the contractor's fuel cell facility in South Windsor, Connecticut. A 40-kW power plant design review was held during the April oral technical review.

The following proposals were prepared and submitted to DOE and GRI:

1. Cost proposal for fabrication of a second verification power plant. Funds were not available to pursue this option.

2. Technical and cost proposal to manufacture and support 50 field test power plants. This proposal was not acted upon during this period.

3. Cost proposal to add verification testing to contract tasks. DOE advised that they would add this effort to the contract.

   The contractor also discussed the need for continuing technological advancement, however, funds were not available to start any program of this nature during this reporting period.

   The contractor reviewed cost projections for quantities of 10,000 units/year with representatives of DOE, GRI, Carnegie Mellon and McKinsey & Company. A preliminary manufactured cost in 1977 dollars was estimated to be $535/kW for the field test configuration in quantities of 10,000/year, dropping to $300-$350/Kw for mature production versions.

NATIONAL BUREAU OF STANDARDS

A number of energy saving demonstrations were performed by the pilot 40-kW power plant operation as part of a total energy system simulating a 16 unit garden apartment.

Visitors included representatives of utilities, R&D agencies, utility commissions, potential action committees, N.Y/N.J port authority, foreign utilities.

4.0 TECHNICAL APPROACH CHANGES

1. At the request of utility field test participants and with DOE/GRI approval, the high grade heat exchanger was changed from one accommodating steam external loop to one compatible with a water external loop.

2. The utilities participating in the field test program expressed a desire that the 40-kW field test power plant be capable of operating in cold weather and in all kinds of weather. The contractor developed a preliminary estimate of the changes required to the power plant. Review of these changes ʻth NASA, DOE and GRI representatives resulted in a plant to incorporate these changes by contract modification.

5.0 VARIANCES OR PROBLEMS

None

6.0 OPEN ITEMS

None

7.0 SUMMARY FORECAST

The contractor forecasts a successful completion of the 40-kW engineering and development program by May 30, 1980 and completion of the draft final report by July 31, 1980.

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